AD-A124 235 A MODEL FOR ON-OFFSHORE SEDIMENT TRANSPORT IN THE SURFZONE(U) NAVAL CIVIL ENGINEERING LAB PORT HUENEME CA J A BAILARD DEC 82 NCEL-TN-1649 1/1

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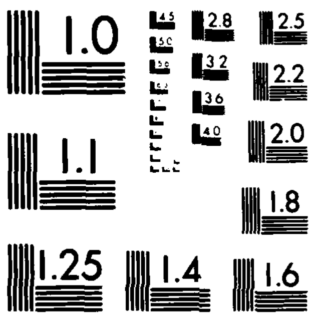

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TN NO: N-1649

TITLE: A MODEL FOR ON-OFFSHORE SEDIMENT TRANSPORT IN THE SURFZONE

AUTHOR: James A. Bailard

DATE: December 1982

SPONSOR: NAVAL FACILITIES ENGINEERING COMMAND

PROGRAM NO: ZR000-01-183 and YF 60.536.091.01.A101

NOTE

NAVAL CIVIL ENGINEERING LABORATORY
PORT HUENEME, CALIFORNIA 93043

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METRIC CONVERSION FACTORS

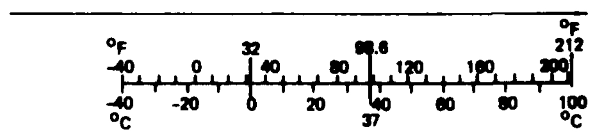
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2,000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1,000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1 REPORT NUMBER TN 1649	2 GOVT ACCESSION NO DN187254	3 RECIPIENT'S CATALOG NUMBER AD-A124 235
4 TITLE (and Subtitle) A MODEL FOR ON-OFFSHORE SEDIMENT TRANSPORT IN THE SURFZONE		5 TYPE OF REPORT & PERIOD COVERED Final; Oct 81 -- Jun 82
		6 PERFORMING ORG REPORT NUMBER
7 AUTHOR(s) James A. Bailard		8 CONTRACT OR GRANT NUMBER(s)
9 PERFORMING ORGANIZATION NAME AND ADDRESS NAVAL CIVIL ENGINEERING LABORATORY Port Hueneme, California 93043		10 PROGRAM ELEMENT PROJECT TASK AREA & WORK UNIT NUMBERS ZR000-01-183, 61152N, YF60.536.091.01.A101, 62760N
11 CONTROLLING OFFICE NAME AND ADDRESS Naval Facilities Engineering Command Alexandria, Virginia 22332		12 REPORT DATE December 1982
		13 NUMBER OF PAGES 53
14 MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15 SECURITY CLASS (of this report) Unclassified
		15a DECLASSIFICATION DOWNGRADING SCHEDULE

16 DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17 DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18 SUPPLEMENTARY NOTES

19 KEY WORDS (Continue on reverse side if necessary and identify by block number)

Sediment transport, surfzone, on-offshore, wave velocity, energetics.

20 ABSTRACT (Continue on reverse side if necessary and identify by block number)

An energetics-based surfzone sediment transport model is evaluated for its ability to predict on-offshore sediment movements using nearshore sediment transport study current meter and beach volume measurements. The magnitude and distribution of pertinent wave velocity moments are also evaluated from the same data set. The latter were found to be linear functions of the significant wave height. Results of the study showed that the current meter data were of insufficient length to evaluate the sediment transport model's validity.

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Naval Civil Engineering Laboratory
A MODEL FOR ON-OFFSHORE SEDIMENT TRANSPORT IN THE SURFZONE (Final) by James A. Bailard
TN-1649 53 pp illus December 1982 Unclassified

1. Sediment transport 2. Surfzone I. ZR000-01-183 II. YF60.536.091.01.A101

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CONTENTS

INTRODUCTION

Waves breaking on a beach cause sediment to be transported both parallel to (longshore) and perpendicular to (on-offshore) a beach. Recognizing the importance of these processes to Navy operations, the Independent Research Program of the Naval Civil Engineering Laboratory (NCEL) has sponsored research to develop improved sediment transport models for the surfzone. The present study deals only with on-offshore transport.

Although on-offshore and longshore sediment transports are manifestations of the same process, past investigations have generally treated them separately for reasons of simplicity. Fortunately, this separate treatment has been relatively successful for the following two reasons:

1. Wave refraction generally causes the waves to have near normal incidence to the beach at breaking.

2. The mean longshore and on-offshore currents are generally much weaker than the oscillatory velocity magnitude.

As a result, the longshore transport has been found to be relatively well modeled (e.g., Inman and Bagnold, 1963; Komar, 1971) as the product of an oscillatory velocity-induced sediment load and a transport velocity proportional to the longshore current. Similarly, the on-offshore transport may be modeled as a balance between gravity, the asymmetry of the oscillatory velocity distribution, and the on-offshore steady current (e.g., Inman and Frautschy, 1966; Bowen, 1980; Bailard, 1981).

Although the above processes have been qualitatively understood for some time, relatively greater progress has been made in quantitatively predicting the longshore transport as opposed to predicting the on-offshore transport. Several aspects of the latter process tend to make modeling efforts more difficult. These include:

1. A breaking wave/bore propagation model suitable for predicting oscillatory velocity asymmetries and mean on-offshore currents inside the surfzone has been lacking.

2. The effect of the downslope component of the sediment load on the on-offshore sediment transport has generally not been adequately represented in the sediment transport model used.

3. The dynamic near-equilibrium of on-offshore transport on a stable beach tends to magnify the importance of second order effects such as the vertical velocity structure or the threshold criteria for sediment movement.

Because of these difficulties, a number of past models have sought to correlate on-offshore sediment transport with average incident wave conditions, without considering many of the details of the fluid-sediment motions. Some examples of this type of approach are discussed in Seymour and King (1982) and include: the wave steepness models by Dean (1973) and Hattori and Kawamoto (1981); the wave height models by Saville (1957), Aubrey (1978) and Short (1978); and the wave power model by Short (1978). A few models have included some degree of detail of the fluid sediment motions. Examples of models which consider wave velocity asymmetry, downslope sediment loads, and mean on-offshore currents include those by Inman and Frautschy (1966), Bowen (1980) and Bailard (1981). These three models are based on adaptations of Bagnold's (1963, 1966) sediment transport model for streams. Bailard's (1981) model is the most complete in that nonnormal wave incidence is permitted as is the presence of longshore currents.

A common aspect of Bowen's (1980) and Bailard's (1981) energetics-based models is the importance of several surfzone velocity moments in determining the direction and magnitude of the on-offshore sediment transport. These moments are defined in terms of idealized monochromatic waves. However, they can be extended to spectral wave inputs using the techniques described in Guza and Thornton (in review). Using Stokes' second-order wave solution and Longuet-Higgins' (1953) bottom streaming model to estimate the wave velocity asymmetry and mean on-offshore

current, respectively, Bowen (1980) and Bailard (1981) were able to qualitatively describe the equilibrium beach profile as a function of the incident wave amplitude a; the wave frequency σ; and sediment fall velocity W (Figure 1). Small amplitude, long period waves were found to produce a steep beach while large amplitude, short period waves were found to produce a flat beach. Large diameter sand grains with high fall velocities were also observed to produce steeper beaches than smaller diameter sand grains with lower fall velocities. These results qualitatively confirm observed beach behavior, but neither the nonlinear wave solution nor the mean current solutions are valid inside the surfzone. Unfortunately other wave shoaling models are equally invalid inside the surfzone due to the dissipation of energy and the generation of turbulence associated with the breaking wave.

Because of the inability of existing wave shoaling models to accurately describe wave velocity asymmetry and mean on-offshore currents inside the surfzone, little is known about these qualities. Two recent studies have described limited field measurements of these quantities (Huntley and Bowen, 1975; Guza and Thornton, in review). These studies suggest that the magnitudes of these quantities may be a function of the incident wave conditions, the beach slope, and the local water depth.

Because of a lack of good field data, very few comparative evaluations have been made of existing on-offshore sediment transport models. Recently, however, a series of large-scale field experiments have been conducted as part of the Nearshore Sediment Transport Study (NSTS). The first of these experiments was conducted at Torrey Pines Beach, Calif., during November 1978. During this time, simultaneous measurements of deepwater wave characteristics, surfzone nearbottom velocity distributions, and beach profile changes were measured. Details of the experiment are described in Gable (1979). Seymour and King (1982) utilized this data set to evaluate a variety of on-offshore sediment transport models. Although none of the models showed great ability to predict the measured beach volume changes, the simple models utilizing incident wave height, wave power, or wave steepness could account for between 25% to 35% of the total variance in the beach volume measurements. The only energetics-based model evaluated was a bedload model developed by Bailard and Inman (1981) which performed rather poorly by comparison.

For two reasons the poor performance of Bailard and Inman's bedload model is not surprising. First, studies by Bowen (1980) and Bailard (1981) have suggested that most of the transport in the surfzone is by nearbottom suspension. Second, the velocity moments controlling on-offshore sediment movements in Bailard and Inman's (1981) bedload model are very sensitive to infrequent data errors that are present on the tapes. Without a careful prescreening of the data, the estimated on-offshore sediment transports must be viewed as suspect.

The success of Bowen's (1980) and Bailard's (1981) total load surfzone models in qualitatively describing the variation of the equilibrium beach slope with wave and sediment characteristics suggested that Bagnold's energetics approach may have some ability to quantitatively predict on-offshore sediment transport. Consequently, a study was initiated to explore the ability of Bailard's (1981) total load sediment transport model to predict daily beach volume changes using data from the NSTS experiment at Torrey Pines Beach, Calif., in November 1978. The objectives of the study were threefold. First, the model was tested in its ability to predict daily beach volume changes using relatively short (1- to 2-hour) surfzone current meter records. Second, a relationship was sought between average values of surfzone velocity moments and incident wave characteristics. Lastly, these average surfzone velocity moments were used to predict on-offshore sediment transport as a function of significant wave height.

SEDIMENT TRANSPORT MODEL

Bailard's (1981) total load sediment transport model is based on an adaptation of Bagnold's (1963, 1966) energetics-based total load sediment transport model for streams. The latter is generalized for time-varying flow over an arbitrarily sloping bottom, resulting in

$$\langle \vec{i}_t \rangle = \rho c_f \frac{\varepsilon_B}{\tan \phi} \left[\langle |\vec{u}_t|^2 \, \vec{u}_t \rangle - \frac{\tan \beta}{\tan \phi} \langle |\vec{u}_t|^3 \rangle \, \hat{i} \right]$$

$$+ \rho c_f \frac{\varepsilon_S}{W} \left[\langle |\vec{u}_t|^3 \, \vec{u}_t \rangle - \frac{\varepsilon_S}{W} \tan \beta \, \langle |\vec{u}_t|^5 \rangle \hat{i} \right] \qquad (1)$$

where $\vec{i}_t$ = instantaneous sediment transport rate vector

ρ = density of water

c_f = drag coefficient of the bed

ε_B = the bedload efficiency factor

ϕ = internal angle of friction of the sediment

$\tan \beta$ = the bed slope

ε_S = suspended load efficiency factor

W = is the fall velocity of the sediment

$\vec{u}_t$ = instantaneous nearbottom fluid velocity vector

$\hat{i}$ = unit vector directed upslope

$\langle\ \rangle$ = time-average

Note that for both the bedload (first bracketed quantity) and the suspended load (second bracketed quantity), the transport consists of a primary component directed parallel to the instantaneous fluid velocity vector and a secondary component directed downslope. The latter is associated with the downslope gravity component of the sediment load.

Figure 2 depicts a plane contour beach with the x-axis directed shoreward and normal to the beach and the y-axis directed parallel to the beach. The slope of the beach is $\tan \beta$. Considering only the on-offshore sediment transport, Equation 1 becomes

$$\langle \vec{i}_x \rangle = \rho c_f \frac{\varepsilon_B}{\tan \phi} \left[\langle |\vec{u}_t|^2 \, \vec{u}_t \cdot \hat{i} \rangle - \frac{\tan \beta}{\tan \phi} \langle |\vec{u}_t|^3 \rangle \right] + \rho c_f \frac{\varepsilon_S}{W} \left[\langle |\vec{u}_t|^3 \, \vec{u}_t \cdot \hat{i} \rangle - \frac{\varepsilon_S}{W} \tan \beta \langle |\vec{u}_t|^5 \rangle \right] \quad (2)$$

Equation 2 is assumed to be valid for any nearbottom velocity field and can be directly used with data from a two-axis (x and y) current meter to predict the time-averaged on-offshore transport rate at the current meter location.

For modeling, it is convenient to use a monochromatic wave representation for the nearbottom water velocity field. Bailard (1981) assumed a velocity field composed of an oscillatory velocity component $\tilde{u}$ oriented at an angle α to the x-axis and a steady velocity component $\bar{u}$ oriented at an angle θ to the x-axis (Figure 2). The total velocity vector $\vec{u}_t$ then becomes

$$\vec{u}_t = (\tilde{u} \cos \alpha + \bar{u} \cos \theta)\, \hat{i} + (\tilde{u} \sin \alpha + \bar{u} \sin \theta)\, \hat{j} \tag{3}$$

In addition, the oscillatory velocity component is assumed to be asymmetrical being composed of a primary component u_m with frequency σ and a secondary harmonic u_{m2} with frequency 2σ so that

$$\tilde{u} \sim u_m \cos \sigma t + u_{m2} \cos 2\sigma t + \ldots \tag{4}$$

Substituting Equations 3 and 4 into Equation 2, Bailard (1981) obtained the idealized on-offshore transport equation

$$\begin{aligned} \langle i_x \rangle = \rho c_f u_m^3 \Bigg\{ & \frac{\varepsilon_B}{\tan \phi} \Bigg[\Psi_1 \cos \alpha + \delta_u{}^3 + \delta_u (\tfrac{1}{2} + \cos^2 \alpha + \delta_v{}^2) \\ & + \delta_v \sin \alpha \cos \alpha - \frac{\tan \beta}{\tan \phi} u_3^* \Bigg] + \frac{u_m}{W} \varepsilon_S \Bigg[\Psi_2 \cos \alpha \\ & + \delta_u u_3^* - \frac{u_m}{W} \varepsilon_S \tan \beta \, u_5^* \Bigg] \Bigg\} \end{aligned} \tag{5}$$

where

$$\delta = \frac{\bar{u}}{u_m} \tag{6}$$

$$\delta_u = \delta \cos \theta \tag{7}$$

$$\delta_v = \delta \sin \theta \tag{8}$$

$$\Psi_1 = \frac{\langle \tilde{u}^3 \rangle}{u_m^3} \tag{9}$$

$$\Psi_2 = \frac{\langle |\vec{u}_t|^3 \, \tilde{u} \rangle}{u_m^4} \tag{10}$$

$$u_3^* = \frac{\langle |\vec{u}_t|^3 \rangle}{u_m^3} \tag{11}$$

$$u_5^* = \frac{\langle |\vec{u}_t|^5 \rangle}{u_m^5} \tag{12}$$

For weak mean currents, Snell's law and the spilling wave hypothesis are sufficient for obtaining estimates of α, u_m, u_3^*, and u_5^* throughout the surfzone as a function of incident wave conditions.† Moreover, a longshore current model (e.g., Longuet-Higgins, 1970) is sufficient for estimating the magnitude of δ_v. Unfortunately, the two skewness parameters Ψ_1 and Ψ_2, as well as the normalized mean onshore current δ_u, cannot be estimated from present surfzone wave shoaling models. Well outside the surfzone, where a rippled bottom generally invalidates the present sediment transport model, Ψ_1, Ψ_2 and δ_u may be estimated from Stokes' second-order wave solution and Longuet-Higgins' (1953) bottom-streaming solution. Assuming negligible longshore currents, weak on-offshore currents and normal incidence, Bowen (1980) and Bailard (1981) used these solutions to obtain the previously discussed solution for the equilibrium beach slope.

Neither Stokes' second-order wave solution nor Longuet-Higgins' (1953) bottom-streaming solution, however, are valid inside the surfzone. Other wave shoaling models are invalid there as well. One of the objectives of this study was to examine measured surfzone values of Ψ_1, Ψ_2, and δ_u using data from the NSTS Torrey Pines experiment (Gable, 1979).

†Note, however, that Guza and Thornton (in review) found that the commonly assumed spilling wave hypothesis did not lead to an accurate estimate of u_m.

In this respect, the present study was a continuation of the study by Guza and Thornton (in review), who showed that the quantities defined in Equation 5 are meaningful only for monochromatic waves incident from a single direction α. On an actual beach the incident waves compose a spectrum with varying energy content at different frequencies and wave angles. As a result, Guza and Thornton (in review) defined equivalent quantities for Ψ_1, Ψ_2, u_m, u_3^* and u_5^*, which may be estimated from the measured current meter data. In addition, a series of six equivalent wave angles, α_1 to α_6, are defined for the different quantities in Equation 5. Equation 5 then becomes (Guza and Thornton, in review)

$$\langle i_x \rangle = \rho c_f u_m^3 \left\{ \frac{\varepsilon_B}{\tan\phi} \left[\Psi_1 \cos\alpha_1 + \delta_u^3 + \delta_u \left(\tfrac{1}{2} + \cos^2\alpha_2 + \delta_v^2\right) + \delta_v \sin\alpha_3 \cos\alpha_3 - \frac{\tan\beta}{\tan\phi} u_3^* \right] + \frac{u_m}{W} \varepsilon_S \left[\Psi_2 \cos\alpha_5 + \delta_u u_3^* - \frac{u_m}{W} \varepsilon_S \tan\beta \, u_5^* \right] \right\} \tag{13}$$

where

$$u_m^2 = 2 \left(\langle \tilde{u}^2 \rangle + \langle \tilde{v}^2 \rangle \right) \tag{14}$$

$$u_m^3 \Psi_1 = \left[\langle \tilde{u}(\tilde{u}^2 + \tilde{v}^2) \rangle^2 + \langle \tilde{v}(\tilde{u}^2 + \tilde{v}) \rangle^2 \right]^{1/2} \tag{15}$$

$$u_m^4 \Psi_2 = \left[\langle |\vec{\tilde{u}}_t|^3 \, \tilde{u} \rangle^2 + \langle |\vec{\tilde{u}}_t|^3 \, \tilde{v} \rangle^2 \right]^{1/2} \tag{16}$$

$$u_m^3 u_3^* = \langle |\vec{u}_t|^3 \rangle = \left\langle \left[\bar{u}_T^2 + \tilde{u}_t^2 + 2\tilde{u}_t \bar{u}_T \cos(\alpha_4 - \theta) \right]^{3/2} \right\rangle \tag{17}$$

$$u_m^5 u_5^* = \langle |\vec{u}_t|^5 \rangle = \left\langle \left[\bar{u}_T^2 + \tilde{u}_t^2 + 2\tilde{u}_t \bar{u}_T \cos(\alpha_6 - \theta) \right]^{5/2} \right\rangle \tag{18}$$

with

$$\tilde{u}_t^2 = \tilde{u}^2 + \tilde{v}^2 \quad \text{and} \quad \bar{u}_T^2 = \bar{u}^2 + \bar{v}^2$$

In addition, the equivalent angles α_1, α_2, α_3, and α_5 may be calculated as follows

$$\tan \alpha_1 = \frac{\langle \tilde{v}^3 + \tilde{u}^2 \tilde{v} \rangle}{\langle \tilde{u}^3 + \tilde{u} \tilde{v}^2 \rangle} \tag{19}$$

$$\tan \alpha_2 = \left(\frac{\langle \tilde{v}^2 \rangle}{\langle \tilde{u}^2 \rangle} \right)^{1/2} \tag{20}$$

$$\sin 2\alpha_3 = \frac{4 \langle \tilde{u} \tilde{v} \rangle}{u_m^2} \tag{21}$$

$$\tan \alpha_5 = \frac{\langle |\vec{u}_t|^3 \tilde{v} \rangle}{\langle |\vec{u}_t|^3 \tilde{u} \rangle} \tag{22}$$

Guza and Thornton (in review) analyzed 2 days of NSTS Torrey Pines data and presented estimated values for Ψ_1, Ψ_2, u_m, δ_u, u_3^*, u_5^*, α_1, α_2, α_3, and α_5 as a function of depth. They found that for the conditions studied $\delta_u \ll 1$, $\delta_v \ll 1$, and α_2 and α_3 were small. In addition, the present study has shown generally that $\cos \alpha_1 \sim 1$ and $\cos \alpha_5 \sim \pm 1$. As a result for conditions such as those at Torrey Pines Beach, Equation 13 can be simplified to

$$\langle i_x \rangle \simeq \rho c_f u_m^3 \left\{ \frac{\varepsilon_B}{\tan \phi} \left[\Psi_1 + \frac{3}{2} \delta_u - \frac{\tan \beta}{\tan \phi} u_3^* \right] + \frac{u_m}{W} \varepsilon_S \left[\Psi_2 + \delta_u u_3^* - \frac{u_m}{W} \varepsilon_S \tan \beta \, u_5^* \right] \right\} \tag{23}$$

where Ψ_1 and Ψ_2 are assumed to be equal to $\Psi_1 \cos \alpha_1$ and $\Psi_2 \cos \alpha_5$, respectively, and can thus take on negative (offshore-directed) values.

Using Equation 23, estimating the on-offshore sediment transport rate becomes a relatively simple matter of estimating u_m, Ψ_1, Ψ_2, δ_u, u_3^*, and u_5^*. One of the objectives of the present study was to determine whether these parameters can be estimated from average gross characteristics of the incident waves.

DATA ANALYSIS

Data Set Description

In November 1978, a month-long field experiment was conducted at Torrey Pines Beach as part of the Nearshore Sediment Transport Study (NSTS). Torrey Pines Beach, Calif., is a plane-contoured beach with a concave profile. The slope of the beach face is approximately 0.05, decreasing to about 0.02 within the surfzone (Figure 3). The sand on the beach is moderately well sorted with a mean diameter of 0.17 mm. The beach exhibits no bar-trough features. The experiment consisted of the simultaneous measurement of incident wave conditions, nearbottom water velocities distributions, sand tracer movements, and beach profile changes. The incident wave climate was measured in 10 meters of water with a linear array of pressure sensors. Nearbottom water velocities were measured using dual-axis (x and y) electromagnetic current meters, while the beach profiles were measured with a rod and transit onshore and a fathometer offshore.

The current meters were placed in a cross-shaped pattern within the nearshore area. Referring to Figure 4, 7 current meters formed a line perpendicular to the beach and ranging in depth from 0.25 meters to 6 meters relative to mean sea level (MSL). Ten other current meters formed a line parallel to the beach at a depth of about 1 meter relative to MSL. The beach profiles were measured at five ranges along the beach. Further details of the measurements and the experiment can be found in Gable (1979).

Model Evaluation

One of the objectives of the present study was to evaluate the ability of Equation 2 to predict daily beach volume changes using NSTS data. The approach used to evaluate Equation 2 was the same as that used by Seymour and King (1982). The daily beach volume changes were computed by integrating the beach profile changes across 100 meters of beach face. The seaward extremity of the integration interval roughly

coincided with the location of the shore-parallel current meters so that a simple box model analysis could be used to estimate the beach volume changes. In the present study the flux of sand into or out of the box was predicted by Equation 2 using the measured current meter data from each shore parallel current meter. The measured volume changes used in the present study are those tabulated by Seymour and King (1982).

Equation 2 has 3 free parameters: the bed friction coefficient c_f, the bedload efficiency factor ε_B, and the suspended load efficiency factor ε_S. In the present study, a value of 0.005 was selected for c_f, based on an analysis of longshore current data at Silver Strand Beach, Calif., (Bailard, 1981). This beach has a bed slope similar to that at Torrey Pines Beach (0.034) and is located 15 miles to the south. On the other hand, Thornton and Guza (1982) examined longshore currents at Torrey Pines Beach and concluded that $c_f = 0.01 \pm 0.01$. As evidenced by the large uncertainty interval, Thornton and Guza concluded that the Torrey Pines data set was not particularly good for estimating the size of c_f.

The bedload and suspended load efficiency factors ε_B and ε_S are the remaining two free parameters in Equation 2. Rewriting Equation 2 to isolate these factors, we obtain

$$\langle i_x \rangle = \varepsilon_B I_A + \varepsilon_S I_B - \varepsilon_S^2 I_C \tag{24}$$

where

$$I_A = \frac{\rho c_f}{\tan \phi} \left[\langle |\vec{u}_t|^2 \vec{u}_t \cdot \hat{i} \rangle - \frac{\tan \beta}{\tan \phi} \langle |\vec{u}_t|^3 \rangle \right] \tag{25}$$

$$I_B = \frac{\rho c_f}{W} \langle |\vec{u}_t|^3 \vec{u}_t \cdot \hat{i} \rangle \tag{26}$$

$$I_C = \frac{\rho c_f}{W^2} \tan \beta \langle |\vec{u}_t|^5 \rangle \tag{27}$$

Equation 24 expresses the on-offshore transport rate in terms of immersed weight transport. The volumetric transport rate Q_x may be related to the immersed weight transport rate $\langle i_x \rangle$ by the following equation

$$Q_x = \frac{\langle i_x \rangle}{(\rho_s - \rho)\, g\, N_o} \tag{28}$$

where ρ_s = density of the sand grains

g = gravity

N_o = "at rest" volume concentration of sediment assumed here to be 0.6

The procedure used to estimate the bedload and suspended load efficiencies ε_B and ε_S was as follows. First, daily estimates of I_A, I_B and I_C were obtained from 64-minute records for each of the 10 shore-parallel current meters. These estimates were averaged together to form a single daily estimate that was assumed to be representative of the general experiment area. Table 1 contains a summary of the estimated values for I_A, I_B, and I_C. Next, a correlation analysis was conducted to determine the lag time between the predicted volume changes and the measured changes. To do this, previously estimated values of $\varepsilon_B = 0.21$ and $\varepsilon_S = 0.025$ obtained from longshore transport data (Bailard, 1981) were used with Equation 24. Following the rationale of Seymour and King (1982), only lag times of zero and 1 day were considered. The maximum correlation ($R^2 = 0.19$) occurred with a lag time of 1 day, as was found by Seymour and King (1982) for a number of other models using the same data set. The lag time result was relatively insensitive to different values of ε_B and ε_S, although R^2 varied as would be expected.

The relatively small value of R^2 (0.19) means that only 19% of the observed variance in the measured beach volume changes is accounted for by the model. By comparison, using the same data set, Seymour and King (1982) found R^2 values as high as 0.35 for a simple model relating the wave steepness to on-offshore sediment movements. Possible reasons for the relatively poor performance of the present model are discussed below.

A nonlinear least-squares estimation procedure (Draper and Smith, 1966), was used to estimate ε_B and ε_S from the data in Table 1. The estimation procedure required constructing a contour map of the mean square error S, defined as

$$S\,(\varepsilon_B\ \varepsilon_S) = \frac{1}{n-2} \sum_{i=1}^{n} (V_{meas} - V_{pred})^2 \qquad (29)$$

where n = number of data pairs (17)

V_{meas} = measured beach volume change with a 1-day lag time

V_{pred} = predicted beach volume change

Figure 5 shows a plot of S versus ε_B and ε_S. The minimum mean square error occurred at $\varepsilon_B = 0.10$ and $\varepsilon_S = 0.02$. These estimates are quite similar in size to those estimated by Bailard (1981) ($\varepsilon_B = 0.21$ and $\varepsilon_S = 0.025$) based on longshore transport data. Figure 5 also shows that 95% confidence limits on ε_B and ε_S. The limits are much broader than for those in Bailard (1981) and reflect, in part, the low degree of correlation between the measured and predicted beach volume changes. In both cases, however, the predicted values of ε_B and ε_S fall within each other's areas of uncertainty.

The low degree of correlation between measured and predicted beach volume changes raises questions about the ability of Bailard's (1981) sediment transport model to predict on-offshore sediment transports. It should be recognized, however, that predicting on-offshore sediment transport rates is a severe test of a model because the net transport represents a small difference between two relatively large instantaneous on and offshore sediment transports. Small biases in either the onshore or offshore direction can significantly influence the predicted direction and magnitude of the net transport. In addition, a sensitivity analysis was performed whereby, for selected days, estimates of the on-offshore transport rate were calculated for consecutive 64-minute segments of time. For a day with moderate waves (November 4), the standard deviation of these estimates was 22% of the predicted mean for four consecutive segments. For a day with large waves (November 12), this value increased to 46% for three consecutive segments. In addition, individual current meters showed a much wider range of variation (up to 800%) between consecutive hours. These results suggest that although

the beach may generally be in a state of near dynamic equilibrium, small changes in the incident wave conditions or the tide may strongly influence short-term local on-offshore movements. As a result, for the data set studied, short current meter records of 1 to 4 hours may not be of sufficient duration to estimate the daily beach volume changes. Alternatively, the model may simply be unable to estimate on-offshore sediment movements. The present data set is insufficient to resolve this question.

Velocity Moment Magnitudes

The above discussion concerned the ability of Equation 2 to predict on-offshore sediment transports. Equation 2, however, requires a full knowledge of the surfzone velocity field and is, therefore, not very useful for modeling. Equation 23 is a greatly simplified version of Equation 2, which is potentially more useful for modeling on-offshore sediment transports. Unfortunately, this equation still contains a number of surfzone velocity moments, about which little is known. These include the wave velocity skewness parameters Ψ_1 and Ψ_2 (Equations 9 and 10), the normalized onshore current δ_u (Equation 7), and the normalized velocity magnitudes u_3^* and u_5^* (Equations 11 and 12).

As previously discussed, only u_m, u_3^*, and u_5^* can be estimated using linear wave theory. For normally incident monochromatic waves and weak mean currents, u_3^* and u_5^* are equal to 0.424 and 0.339, respectively, while for a Gaussian input with the same total variance their values become 0.562 and 1.13, respectively (Guza and Thornton, in review). Guza and Thornton found that a Gaussian distribution was most nearly correct.

Assuming wave saturation and spilling waves, linear wave theory suggests that

$$u_m = \frac{\gamma}{2}\sqrt{g\ h} \tag{30}$$

where $\gamma = H/h$

h = local water depth

H = local wave height

Equation 30 suggests that u_m should decrease from a maximum at the breakpoint to zero at the beach. In fact, field measurements show (Guza and Thornton, in review) that u_m was almost constant across the surfzone, due to the presence of low frequency surf beat motions within the inner part of the surfzone. The remaining parameters in Equation 23 (Ψ_1, Ψ_2, and δ_u) are zero for linear waves but nonzero for nonlinear waves. Measurements (Huntley and Bowen, 1975, Guza and Thornton, in review) have shown that they are in fact nonzero under actual field conditions and may vary in magnitude and sign with varying incident wave conditions.

One of the objectives of the present study was to investigate the magnitudes of these surfzone parameters using the NSTS Torrey Pines data set and determine whether their magnitudes and distributions across the surfzone could be estimated from incident wave conditions. Values for the parameters Ψ_1, Ψ_2, δ_u, u_3^* and u_5^* were estimated from 64-minute-long records for each of the seven shore perpendicular current meters closest to shore. Because of the variability of these quantities, mean surfzone values were obtained by averaging the results of all seven current meters. Table 2 is a summary of these average surfzone velocity parameters and the incident wave characteristics for each of the 9 days investigated. The wave characteristics were obtained from Guza and Thornton (1980; in review) who analyzed pressure sensor records measured in 10 meters of water. In addition, Seymour and King (1982) reported significant deep water wave steepnesses for each day. These too are tabulated in Table 2.

Linear and second-order wave theory suggests that the even velocity moments u_m, u_3^*, and u_5^* should be related to the significant wave height, while the odd velocity moments Ψ_1, Ψ_2, and δ_u should also be related to the deep water wave steepness and the average beach slope. Recent studies of surfzone wave dynamics by Wright *et al.* (1978, 1982), Guza and Thornton (1982), Bowen (1980), Huntley and Bowen (1975) and others suggest that long period surfzone motions due to edge waves, surf beat and other infra-gravity wave motions may influence nearshore velocity fields and the resulting nearshore topography. The amplitudes of these

motions are thought to be sensitive to a surf similarity parameter ε introduced by Battjes (1974), Guza and Inman (1975), and others. The parameter is defined as

$$\varepsilon = a\,\sigma^2/g\,\tan^2\beta \tag{31}$$

where a = half the breaking wave height

For small values of ε, less than 2.0 to 2.5, reflective conditions with surging breakers are observed and subharmonic edge wave generation may be present. For larger values of ε, dissipative conditions should prevail, and surf beat may be present.

For the conditions of Torrey Pines Beach, dissipative conditions prevailed, with spilling waves and a wide surfzone. The range of significant wave heights varied from 55 to 140 cm; however the peak wave period varied much less, ranging from approximately 10 to 14 seconds. The variation in mean beach slope during the experiment was also very small, so that the slope was approximately a constant 0.02. As a result, the deep water wave steepness H_S/L_o and the surf similarity parameter ε were primarily a function of the significant wave height H_S. This suggested that for the Torrey Pines data set, a relationship might be sought between all of the relevant surfzone velocity moments and the significant wave height H_s.

Figures 6 through 11 show plots of mean surfzone values of Ψ_1, Ψ_2, δ_u, u_m, u_3^* and u_5^* versus H_s. Lacking more data, a linear relationship was sought between variables; the linear regression lines are shown in each figure. These lines are described by the following equations:

$$\Psi_1 = 0.303 - 0.00144\,H_s \tag{32}$$

$$\Psi_2 = 0.603 - 0.00510\,H_s \tag{33}$$

$$\delta_u = 0.458 - 0.00157\,H_s \tag{34}$$

$$u_m = 31.9 + 0.403\,H_s \tag{35}$$

$$u_3^* = 0.548 + 0.000733\,H_s \tag{36}$$

$$u_5^* = 1.50 + 0.00346\,H_s \tag{37}$$

where u_m is measured in cm/sec and H_s in cm.

Figures 6 through 11 also suggest that for the conditions found at Torrey Pines Beach, Ψ_1, Ψ_2 and δ_u decrease markedly with increasing wave height. This is in direct contrast to Stokes' second-order wave solution and Longuet-Higgins' (1953) bottom-streaming solutions, which predict increasing values of these variables for increasing wave height. The remaining parameters, u_m, u_3^*, and u_5^*, behaved more as would be predicted by linear wave theory. The mean orbital velocity magnitude u_m was found to increase with increasing wave height, while u_3^* and u_5^* were relatively constant. Typical values of u_3^* and u_5^* were 0.6 and 1.2, respectively (very close to the theoretical values based on a Gaussian wave distribution).

Velocity Moment Distributions

While the average surfzone magnitudes of the different velocity moments discussed above are critical in determining general on-offshore sediment movements, spatial details of these movements are reflected by the distribution of the moments across the surfzone. In order to examine these distributions, it was first necessary to normalize the moments by appropriate quantities. For the variables Ψ_1, δ_u, u_m, u_3^*, and u_5^*, the mean surfzone value of each variable was an appropriate normalizing quantity. The skewness parameter Ψ_2 was more difficult because its mean value changed sign. As a result, a new variable Ψ_2' was defined as follows:

$$\Psi_2' = \Psi_2 - \bar{\Psi}_2 \tag{38}$$

This variable was then normalized by its standard deviation and defined as

$$\Psi_2'sd = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} \Psi_2'^2} \tag{39}$$

where n = number of days examined

Figure 12 shows a plot of $\Psi_2'sd$ versus significant wave height.

Figures 13 through 18 are plots of the surfzone distribution of the normalized parameters $\hat{\Psi}_1$, $\hat{\Psi}'_2$, $\hat{\delta}_u$, $\hat{u}_m$, $\hat{u}^*_3$, and $\hat{u}^*_5$ as a function of the normalized surfzone position x*, which is defined as the distance from shore divided by the nominal surfzone width. For the present study, the surfzone width was taken as the distance from the breakpoint to the still water shoreline. Moreover, the breakpoint depth was assumed to be equal to $H_s/0.78$. A cursory examination of Figures 13 to 18 reveals that there is considerably more scatter in the plots of $\hat{\Psi}'_2$ and $\hat{\delta}_u$ than in the plots of the other variables. These two parameters are closely related and the variability in $\hat{\Psi}'_2$ is believed to primarily be a reflection of the variability in $\hat{\delta}_u$. As previously mentioned, the mean on-offshore current was the most variable surfzone quantity examined. This was again the case in the surfzone distributions.

Considering the surfzone distributions of $\hat{\Psi}_1$, $\hat{u}_m$, $\hat{u}^*_3$, and $\hat{u}^*_5$ (Figures 13, and 16 through 18), each variable appears to have a predictable distribution. Whereas $\hat{\Psi}_1$, $\hat{u}^*_3$, and $\hat{u}^*_5$ increase with increasing distance from shore, $\hat{u}_m$ is seen to decrease with increasing distance from shore. The data for $\hat{\Psi}'_2$ and $\hat{\delta}_u$ are so scattered that no definite trends are evident.

ON-OFFSHORE TRANSPORT SIMULATION

The simplified on-offshore sediment transport model Equation 23 was found to contain several surfzone velocity moments about which little was known. These moments included the wave velocity skewness parameters Ψ_1 and Ψ_2, the mean on-offshore current δ_u, the orbital velocity magnitude u_m, and the normalized total velocity magnitudes u^*_3 and u^*_5. For the wave and beach conditions present during the NSTS Torrey Pines experiment, average surfzone values for those parameters were found to be linearly related to the significant wave height H_s through Equations 32 to 37. Combining Equation 23 with Equations 32 to 37, the average surfzone on-offshore transport rate and direction can be predicted as a function of the significant wave height and the sediment fall velocity. The

other free parameters in Equation 23 include the bed drag coefficient c_f, the bedload efficiency ε_B, and the suspended load efficiency ε_S. For the present study these variables were assumed to be equal to 0.005, 0.21, and 0.025, respectively. These values were selected on the basis of an analysis of field and laboratory longshore transport data as discussed by Bailard (1981). Other similar values can be selected without qualitatively changing the results.

Figure 19 shows a plot of the predicted on-offshore sediment transport rate as a function of the significant wave height. The sediment fall velocity was assumed to be equal to 4 cm/sec, which is appropriate for the sand found at Torrey Pines Beach. The bedload-transport rate is depicted by the dashed line, the suspended load transport rate by the dotted line, and the total load transport rate by the solid line. Figure 19 suggests that, for conditions similar to those at Torrey Pines Beach during the NSTS experiment, sand is moved onshore when the significant wave height is less than approximately 90 cm and offshore when it is greater. The maximum onshore transport rate (0.8 $m^3 m^{-1}$ day^{-1}) occurs when H_s is equal to approximately 59 cm. For waves with a significant wave height greater than approximately 150 cm, the transport rate is larger by a factor of 10 and directed offshore. Under most conditions, the predicted bedload and suspended load transports are both in the same direction. Near the null point ($H_s \sim 90$ cm), however, the bedload is directed offshore while the suspended load is directed onshore.

Qualitatively, Figure 19 tends to confirm some aspects of observed beach behavior. During prolonged periods of small waves, a beach is seen to slowly accrete. With the appearance of the first large swell, however, the beach can cut back dramatically within a few days. Figure 19 supports this observation. In addition, Figure 19 qualitatively supports Short's (1978) observations at several Australian beaches that the neutral point wave height separating accretion from erosion was equal to 120 cm. Although the present study suggests a neutral point wave height of 90 cm, the magnitudes are similar.

Because the wave velocity characteristics are independent of grain size, the effect of different sediment fall velocities on the total load sediment transport rate may be predicted as well (Figure 20). Increasing

the fall velocity is seen to decrease the magnitude of the on-offshore transport rate without seriously affecting the value of the neutral point wave height. As a result, beaches with fine sand would be expected to experience greater changes in volume than equivalent beaches with coarse sand.

DISCUSSION

The applicability of these results to other sites and to other wave conditions is unknown; however, it is hypothesized that the results may be relatively site and time specific. Generally speaking, for monochromatic waves and plane contour beaches, the surfzone hydrodynamics should be a function of the incident wave height, direction, and period, as well as the beach slope. For random waves, the shapes of the energy and directional spectrums may also be important. During the NSTS Torrey Pines experiment, the waves were almost normally incident with a near uniform period. Moreover the beach slope changed little during the month. The only parameter that varied to any significant degree was the wave height, which varied by a factor of 3. As a result, Figures 19 and 20 cannot be directly extended to more general conditions. Neglecting for a moment the effects of incident wave angle and wave period, physical reasoning suggests that there should be a family of curves similar in shape to those in Figures 19 and 20 that vary with beach slope. The primary difference between different curves would be the position of their neutral point wave height. For flat beaches typical of large wave conditions, the neutral point wave height would be larger, while for steeper beach conditions the neutral point wave height would be smaller. Figures 19 and 20 are believed to represent transition conditions. Partial support for this hypothesis is provided in the study by Aubrey (1978), who found that future beach profiles at Torrey Pines Beach were best predicted when the existing beach profile shape and the incident wave height were known. Clearly, more data sets with a wider range of beach slope and wave conditions are needed to develop a useful beach profile predictive capability.

Further discussion is also needed concerning possible errors in the estimated surfzone velocity moments. The odd moment quantities Ψ_1, Ψ_2, and δ_u, in effect, represent small differences between large numbers, so they are especially sensitive to small errors in the measured current meter data. Because of this sensitivity, considerable care was exercised in prescreening the data. The quantity u_5^* was found to be particularly sensitive to data errors and was used as an indicator of bad sections of data. In spite of this care, the data itself could be subject to an inherent bias due to current meter inaccuracies.

One error in particular may be that the mean on-offshore currents were a manifestation of a current meter rectification process.* Some evidence, however, suggests that rectification may not have been too significant. First, if rectification were important the mean offshore current might be expected to be a function of u_m. The latter was found to be relatively constant across the surfzone, while the mean offshore currents varied significantly. This tends not to support a rectification hypothesis. Moreover, Wright et al. (1978) reported measuring onshore currents in the upper part of the water column inside the surfzone and offshore currents near the bottom. These measurements were made with small ducted fan current meters unlike the electromagnetic current meters used in the NSTS experiments and, presumably, would not be subject to the same rectification characteristics. Nevertheless, until more exhaustive studies are done on the response of the electromagnetic current meters, the magnitudes and directions of the mean on-offshore currents must be suspect.

It is disappointing that the present sediment transport model is not more accurate at predicting the measured beach volume changes. The reason for its lack of accuracy is unknown. The variability in the estimated on-offshore transport rates between consecutive hourly data sets suggests, however, that the on-offshore transport rate may vary significantly on an hourly basis due to small changes in the incident wave field and the tide. The latter changes the position of the surfzone relative to the existing beach profile, which can significantly

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*From personal communication with R. T. Guza and D. G. Aubrey.

alter the breaking wave characteristics. As a result, it may be intrinsically difficult to test the capability of an on-offshore sediment transport model to predict daily beach volume changes using current meter records of very limited duration.

In addition, some of the measured beach volume changes seem to be anomalous in light of our present limited knowledge. In particular, the large on-offshore rates of sand movements during periods of small waves on November 6, 7, and 20 are difficult to understand. It would appear that wave energy should have been insufficient to generate this volume of sediment transport. One possible explanation may be a temporary local convergence or divergence of the longshore transport rate. Another explanation may be inaccuracies in the beach profile measurements.

CONCLUSIONS

Based on the results of this study, the following conclusions can be made:

1. A thorough evaluation of Bailard's (1981) surfzone sediment transport model using daily beach volume measurements was not possible due to inadequate surfzone current meter record lengths and to possible inaccuracies in the beach profile measurements.

2. Predicting beach volume changes using a highly simplified form of Bailard's (1981) surfzone sediment transport model appears promising. Analysis of additional surfzone current meter data sets having different wave and beach slope characteristics is necessary before a useful predictive capability can be developed.

3. Average surfzone wave velocity moments were found to be a linear function of significant wave height. Additional data sets are needed to determine their relationships to wave period and average beach slope.

4. Except for the mean on-offshore current $\hat{\delta}_u$, and the second skewness parameter $\hat{\Psi}_2$, the normalized surfzone distributions of the wave velocity moments appear to exhibit a predictable form of behavior.

5. Without analysis of additional data sets, the degree of generality of these results is unknown.

RECOMMENDATIONS

The following research is needed to develop a more generally valid on-offshore sediment transport model:

1. Investigate pertinent surfzone velocity moments on beaches with significantly different beach slopes and wave periods than those encountered at Torrey Pines Beach. The NSTS Leadbetter Beach data set does provide a beach with a steeper beach slope, so this would be a likely first candidate.

2. The significance of ignoring threshold of motion effects in the present model must be critically evaluated.

3. A more detailed treatment of the drag coefficient c_f may be warranted. Ideally, the coefficient should be estimated from longshore current data.

4. Sand tracer studies over a very limited area (several meters) in conjunction with a single current meter might be beneficial in evaluating potential sediment transport models.

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Table 1. Estimated and Measured Beach Volume Changes and Incident Wave Characteristics

Day (Nov 1978)	I_A (dyne cm^{1} sec^{-1} x 10^{6})	I_B (dyne cm^{1} sec^{-1} x 10^{4})	I_C (dyne cm^{1} sec^{-1} x 10^{4})	V_{pred} (m^3 m^{1} day^{-1})	V_{meas} (lagged 1 day) (m^3 m^{1} day^{-1})
4	9.87	3.76	4.00	0.72	0.21
5	-14.8	1.18	6.42	0.32	-0.28
6	-9.78	0.65	3.05	0.02	-8.2
7	10.2	2.54	1.78	0.52	9.3
8	-17.5	0.66	1.94	-0.27[a]	1.45
10	-61.5	-10.6	10.2	-2.41[a]	1.08
11	-115	-15.6	12.1	-3.74[a]	1.08
12	-121	-16.1	21.6	-3.9	-13.4
13	-5.53	2.47	6.62	0.36	0.05
14	15.7	5.05	5.72	1.0	3.9
15	12.1	6.00	4.92	1.12	-2.05
16	-4.32	0.86	1.99	0.10	1.05
17	11.3	4.10	4.20	0.79[a]	0.78
18	-1.36	3.21	5.50	0.52[a]	0.78
19	1.83	2.00	4.25	0.34	-1.99
20	-33.0	-2.84	5.00	-0.79	11.2

[a]Estimated as half the 2-day change.

Table 2. Average Surfzone Velocity Parameters and Incident Wave Characteristics

Date (Nov 1978)	H_s (cm)	S	Ψ_1	Ψ_2	δ_u	u_m (cm sec^{-1})	u_3^*	u_5^*
4	55	0.00126	0.206	0.204	-0.131	58.2	0.550	1.25
6	65	0.00148	0.197	0.240	-0.124	59.2	0.603	1.20
7	59	0.00117	0.234	0.362	-0.088	51.8	0.594	1.35
10	101	0.00163	0.097	-0.019	-0.160	69.8	0.731	1.26
11	99	0.00303	0.106	-0.152	-0.250	78.4	0.687	1.11
12	140	0.00341	0.134	-0.035	-0.210	87.2	0.574	0.940
13	91	0.00124	0.222	0.326	-0.100	69.3	0.587	1.27
17	62	0.00194	0.232	0.352	-0.081	56.9	0.574	1.24
19	73	0.00128	0.223	0.350	-0.070	56.1	0.574	1.28

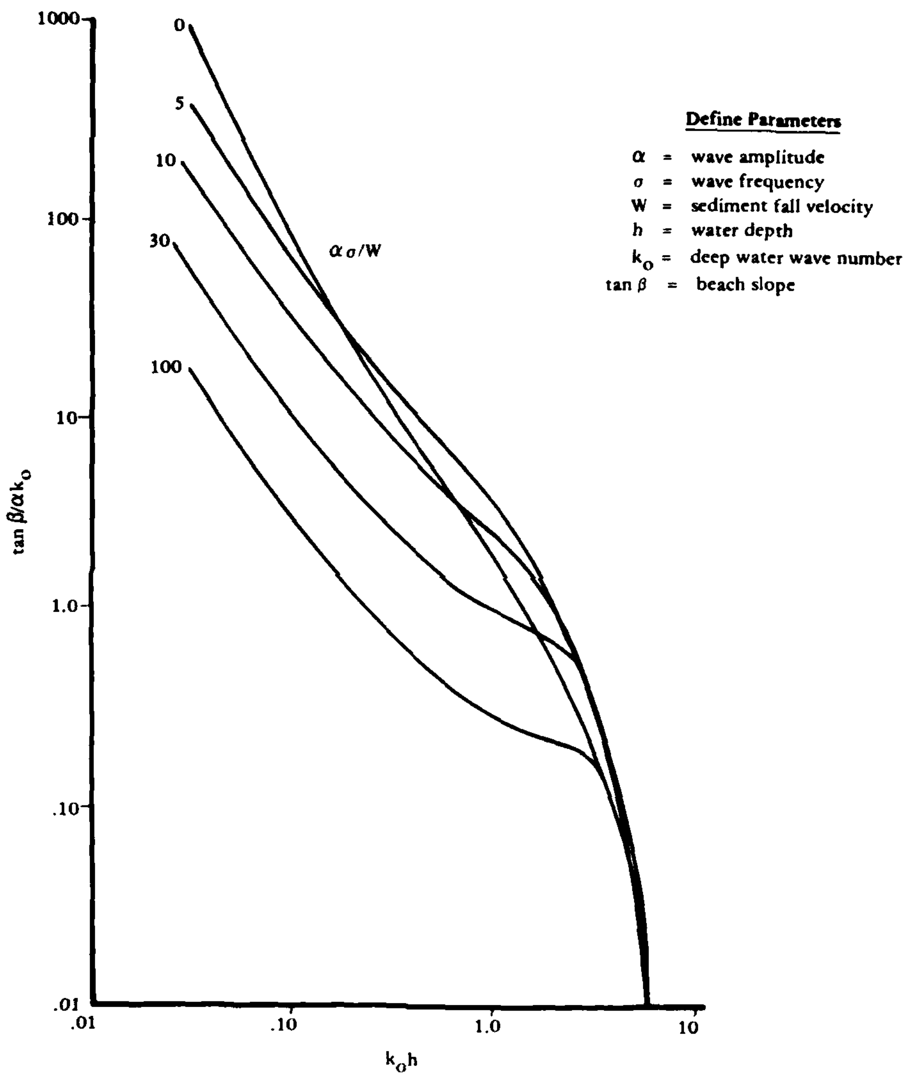

Figure 1. Predicted normalized equilibrium beach slope, tan β/ak_o, as a function of the normalized depth $k_o h$ and the wave amplitude parameter $a\sigma/W$ (from Bailard, 1981).

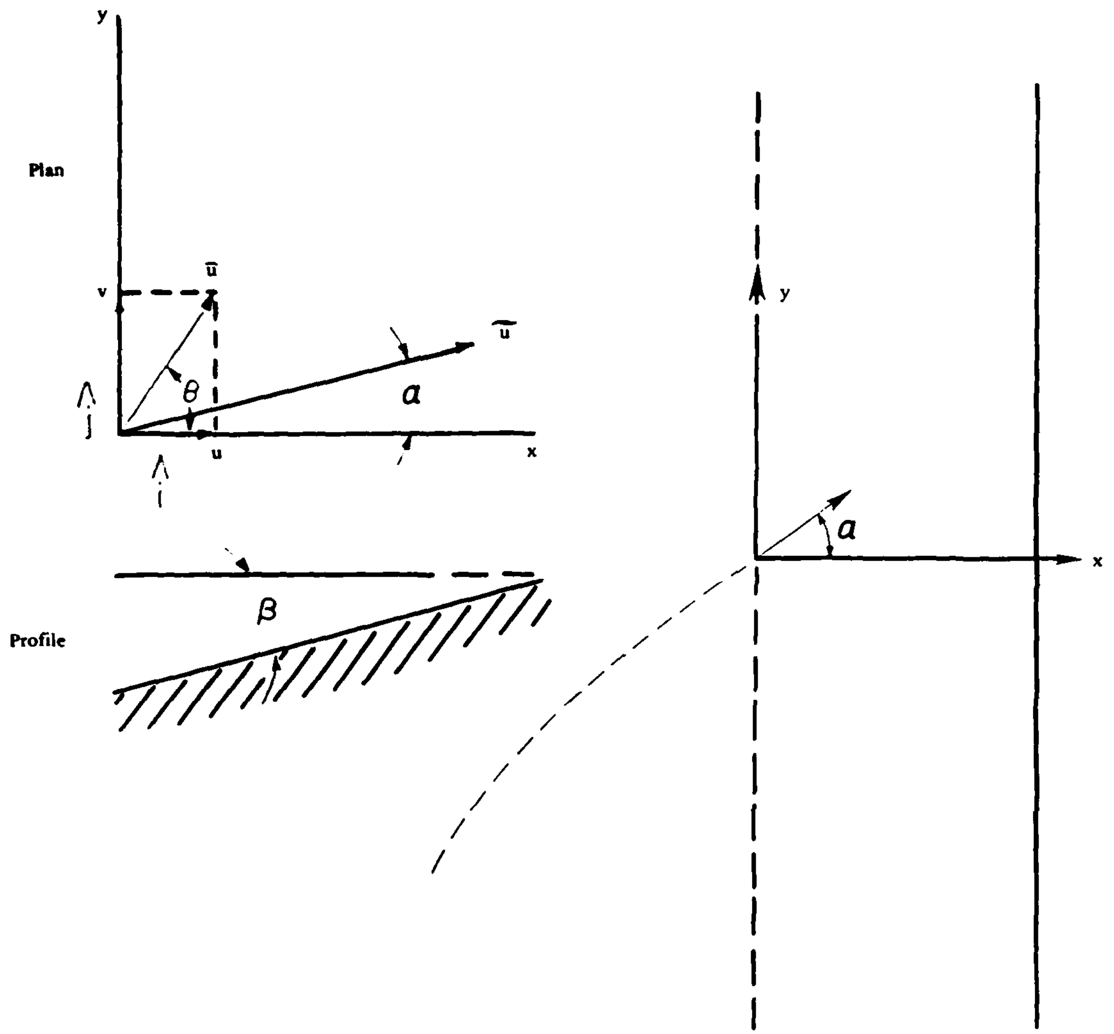

Figure 2. Schematic diagram showing the position of the beach (solid line), the breakpoint (dashed line), the wave angle α and the oscillatory and steady water velocities $\tilde{u}$ and $\bar{u}$ (from Bailard and Inman, 1980, with permission).

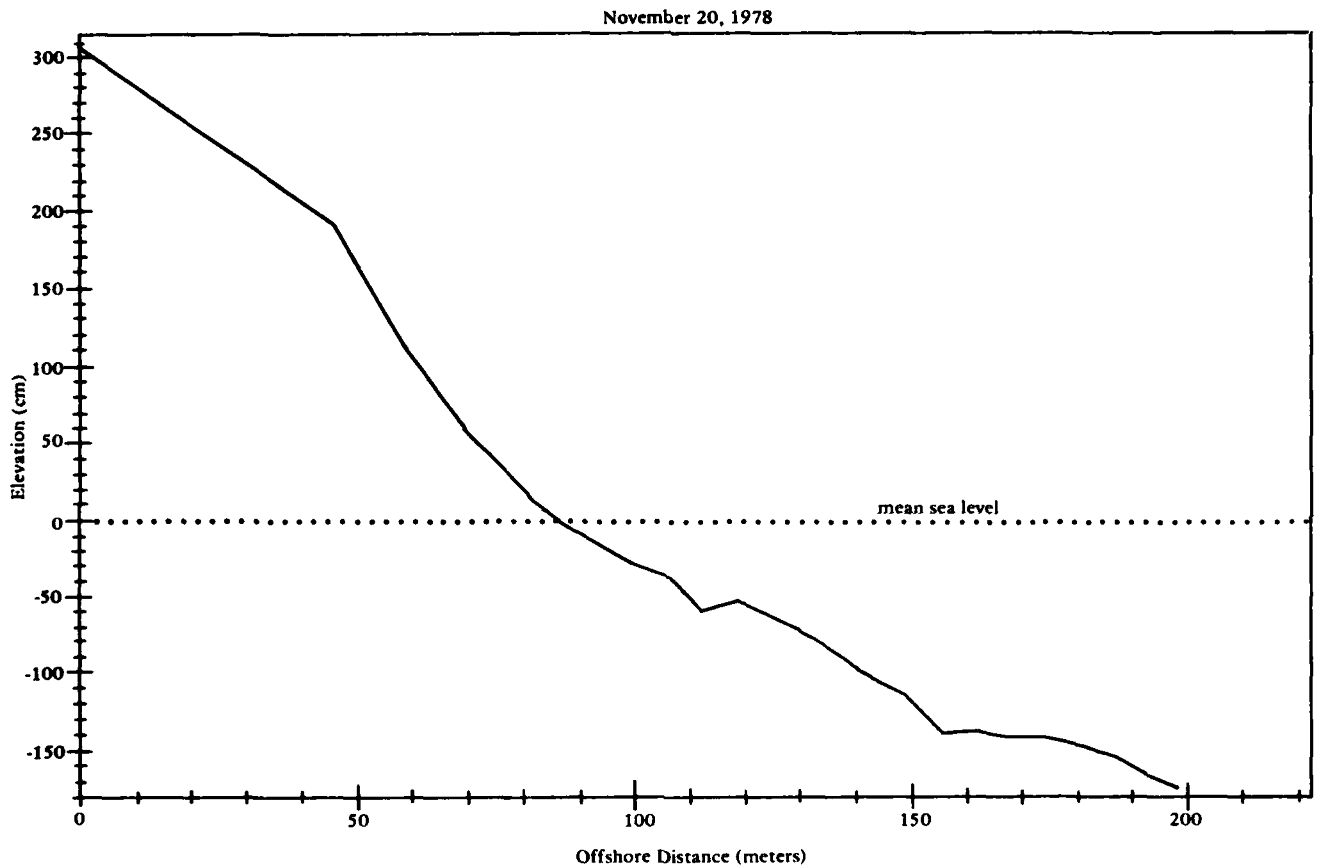

Figure 3. Representative beach profiles for Torrey Pines Beach measured on November 20, 1978 (adapted from Guza and Thornton, NCEL Contract Report).

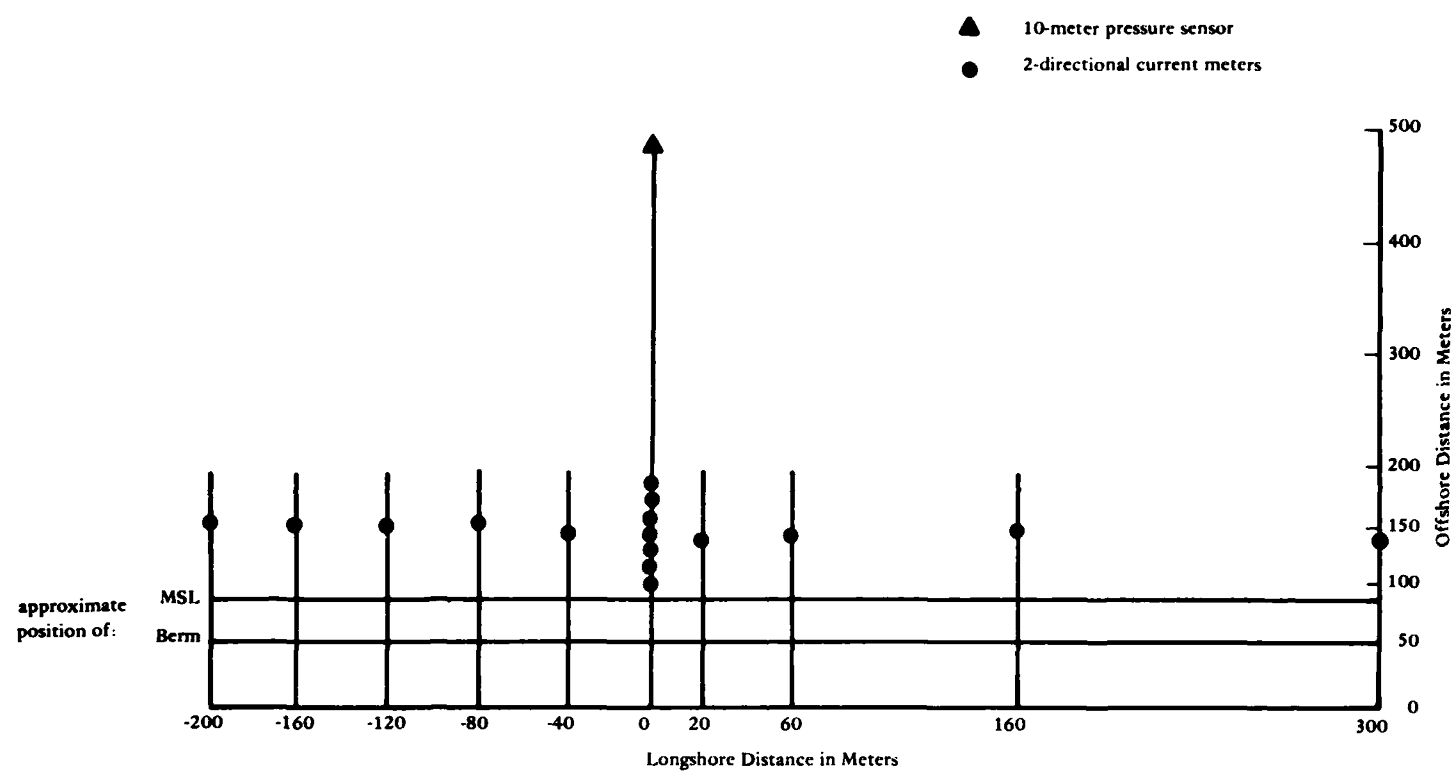

Figure 4. Relative current meter and pressure sensor positions for the NSTS Torrey Pines experiment (adapted from Seymour and King, 1982).

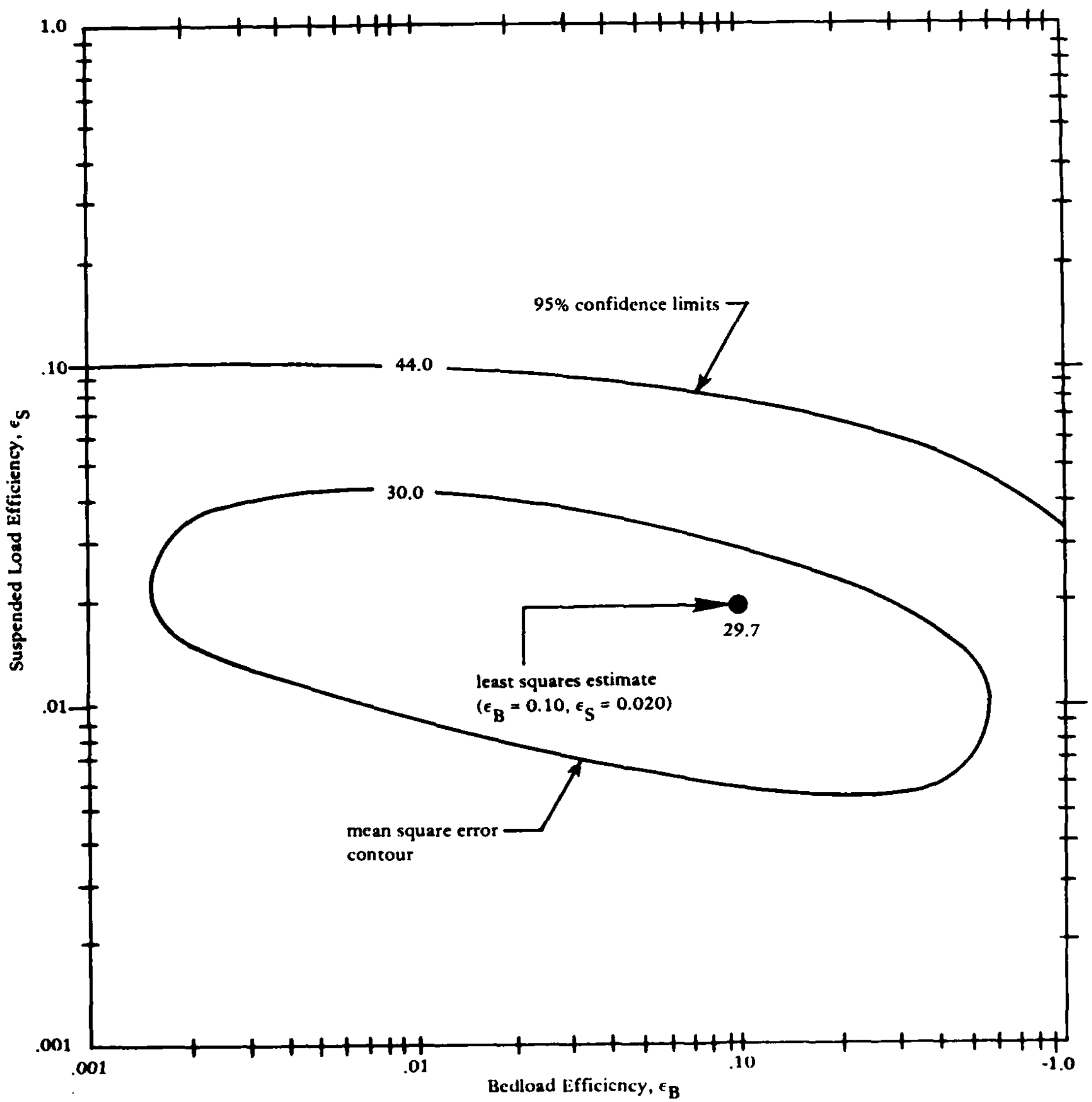

Figure 5. Least squares estimated bedload and suspended load efficiency factors, ϵ_B and ϵ_S.

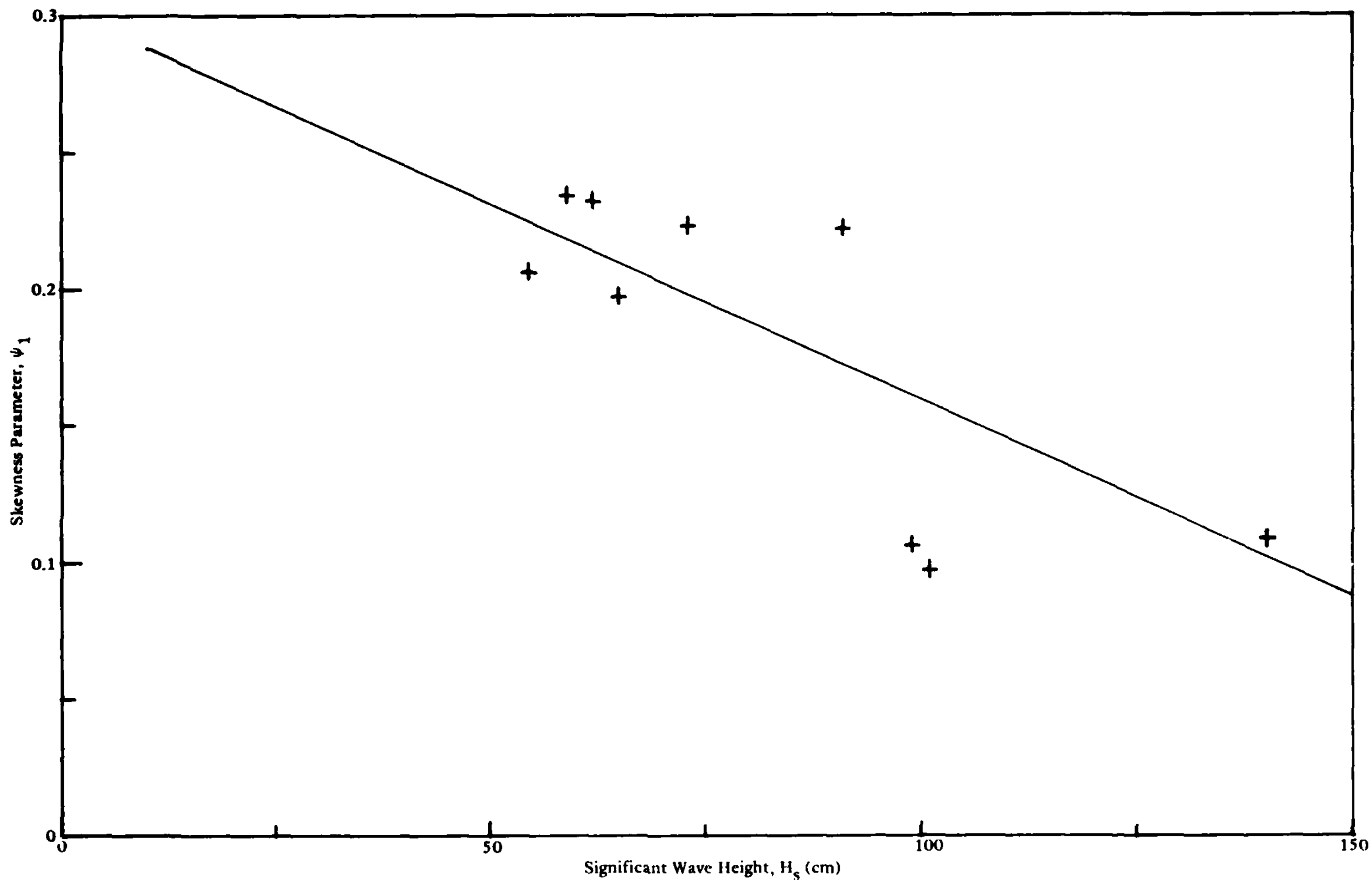

Figure 6. Average surfzone values of the skewness parameter ψ_1 versus significant wave heights computed from single 64-minute current meter records. The straight line is a least-squares fit to the data.

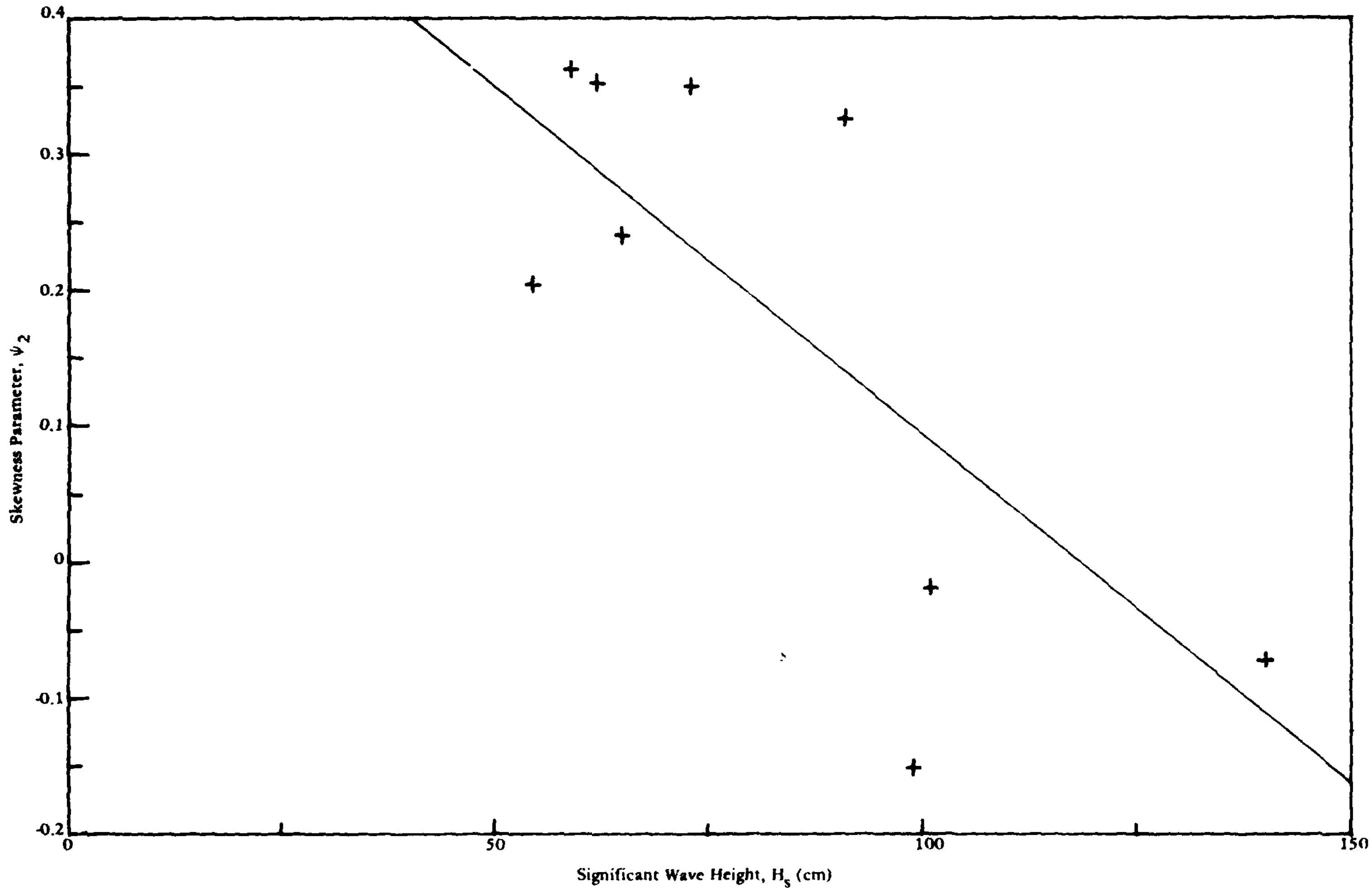

Figure 7. Average surfzone values of the skewness parameter ψ_2 versus significant wave height computed from single 64-minute records. The straight line is a least-squares fit to the data.

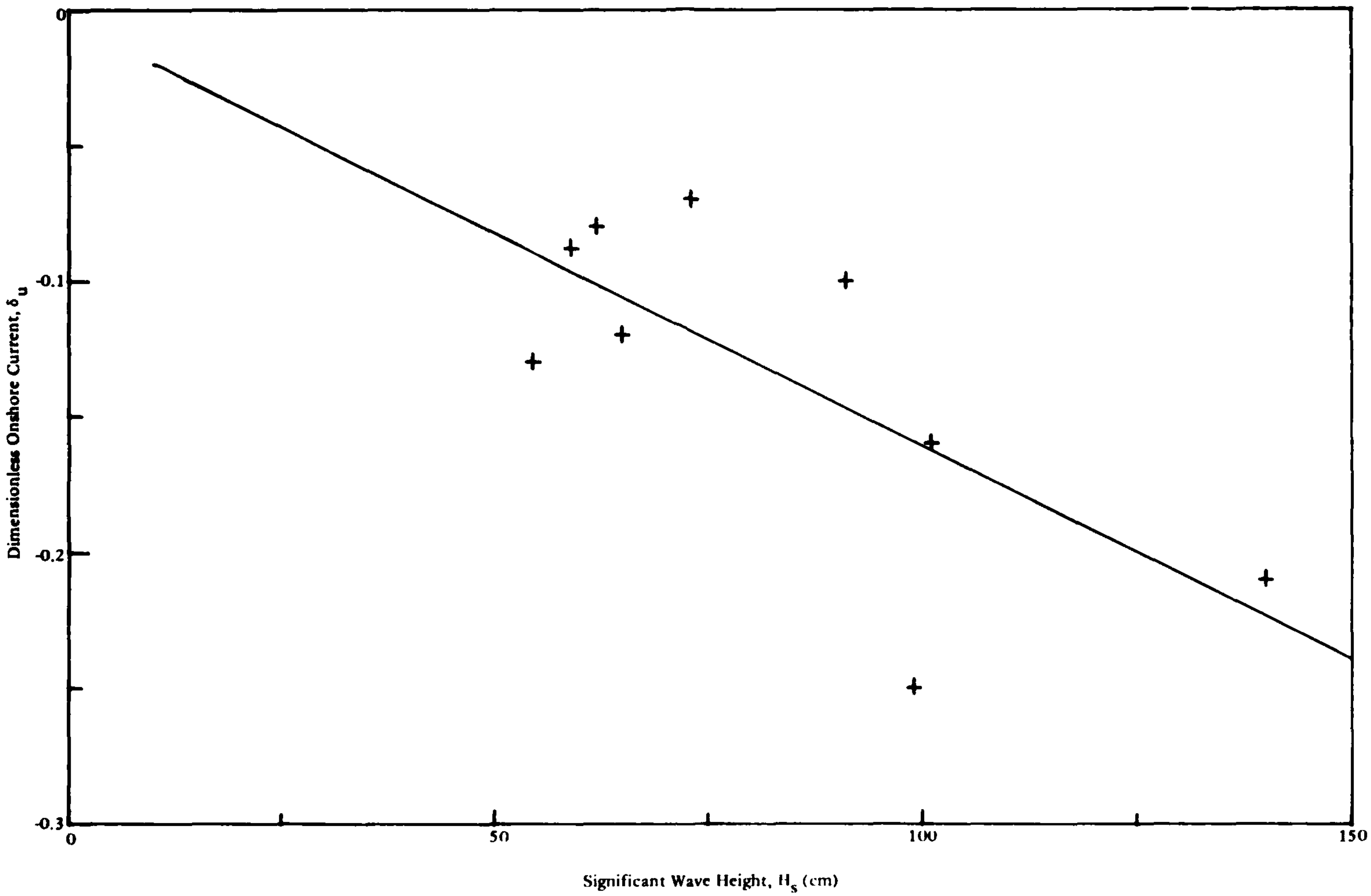

Figure 8. Average surfzone values of the normalized mean onshore current δ_u versus significant wave height computed from single 64-minute records. The straight line is a least-squares fit to the data.

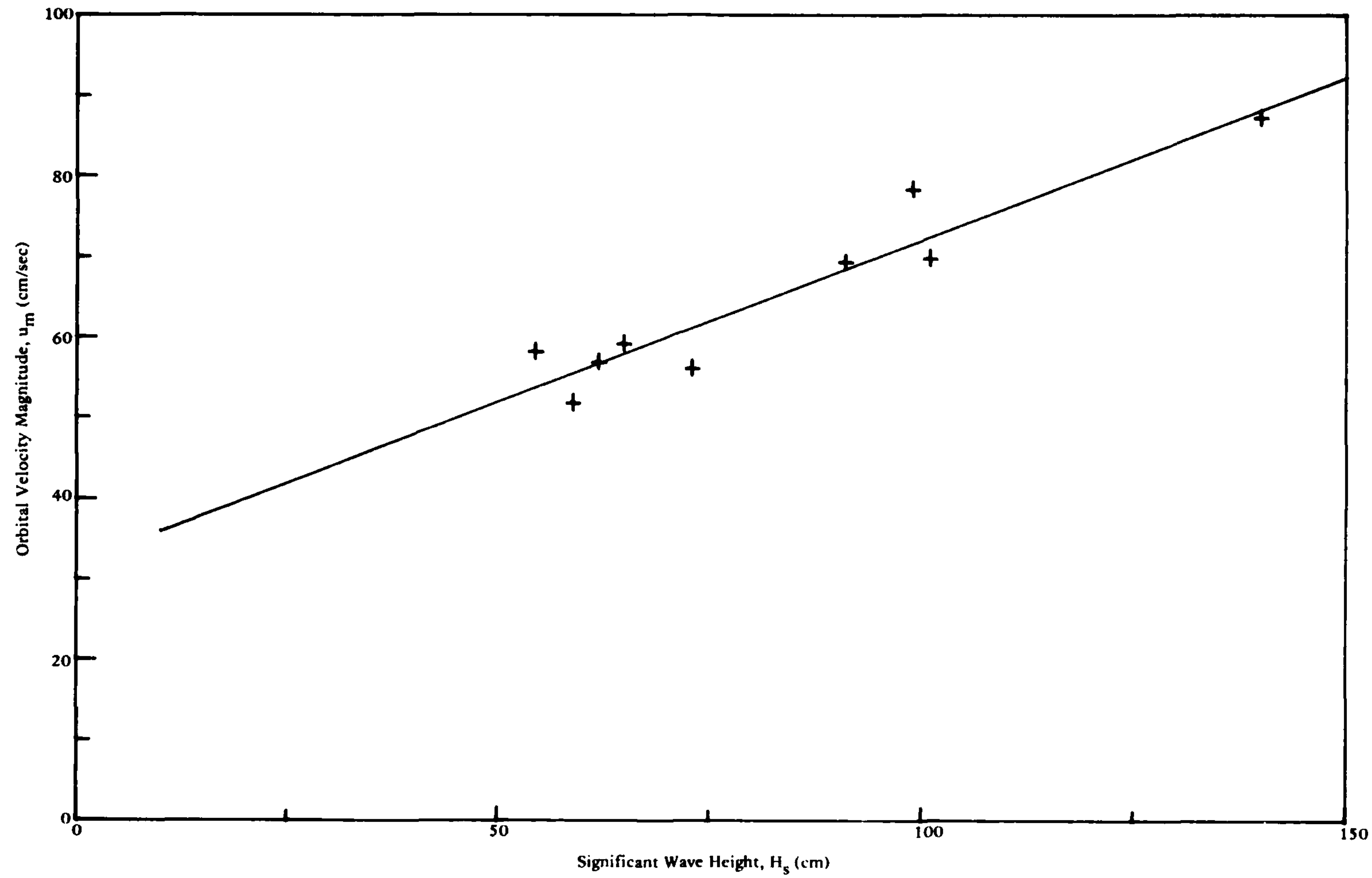

Figure 9. Average surfzone values of the orbital velocity magnitude u_m versus significant wave height computed from single 64-minute records. The straight line is a least-squares fit to the data.

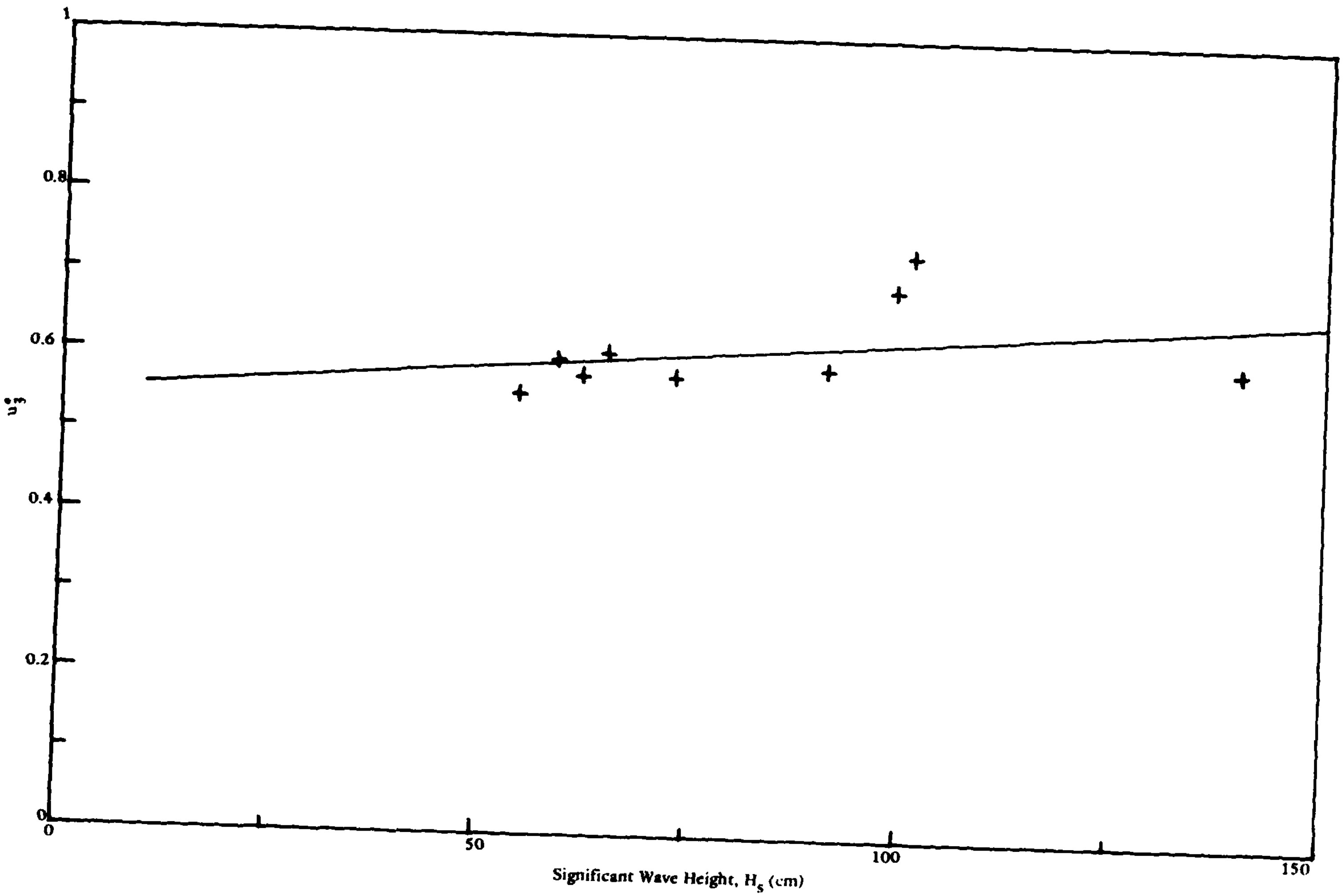

Figure 10. Average surfzone values of u_*^3 versus significant wave height computed from single 64-minute records. The straight line is a least-squares fit to the data.

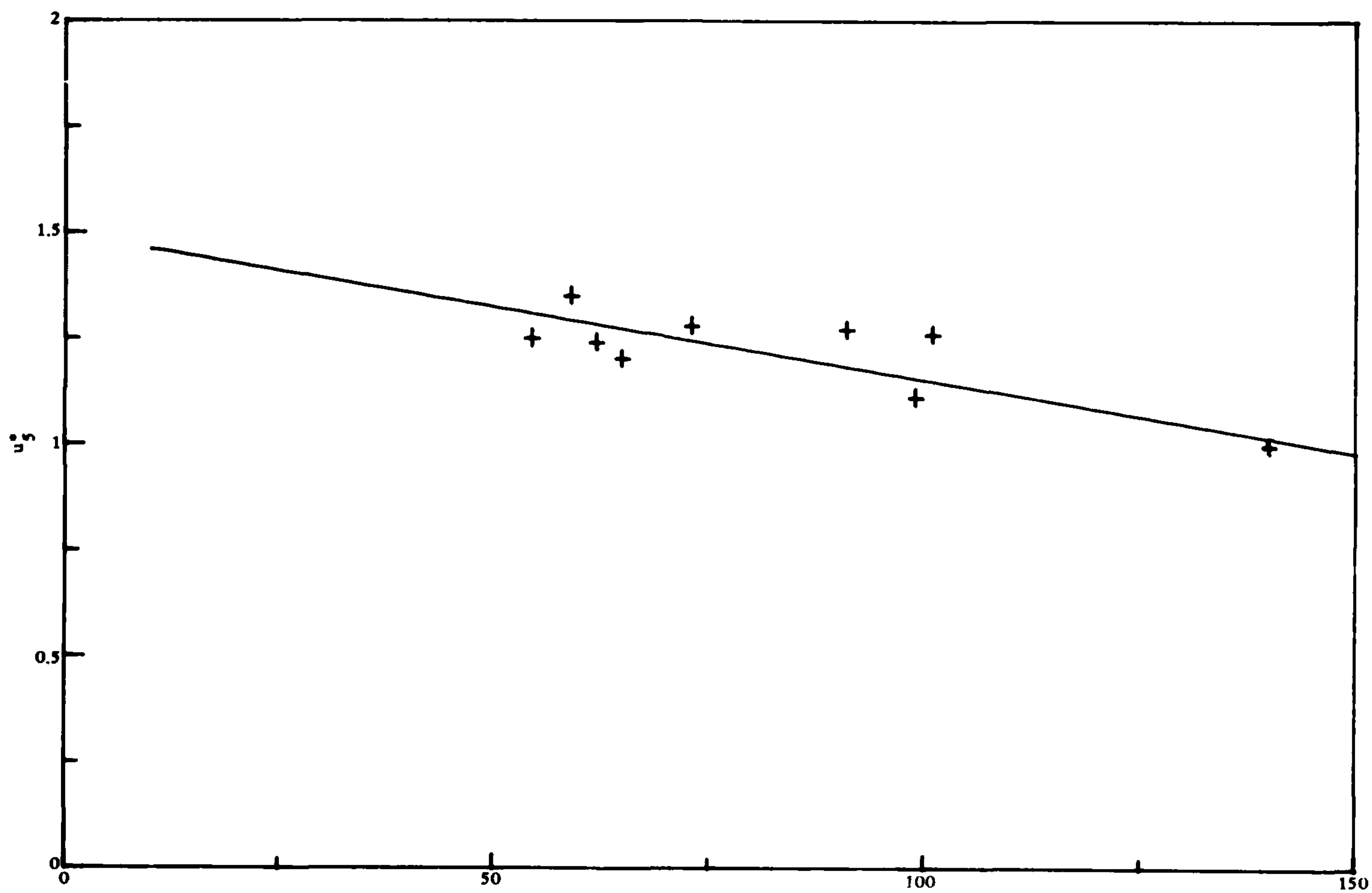

Figure 11. Average surfzone values of u_5^* versus significant wave height computed from single 64-minute records. The straight line is a least-squares fit to the data.

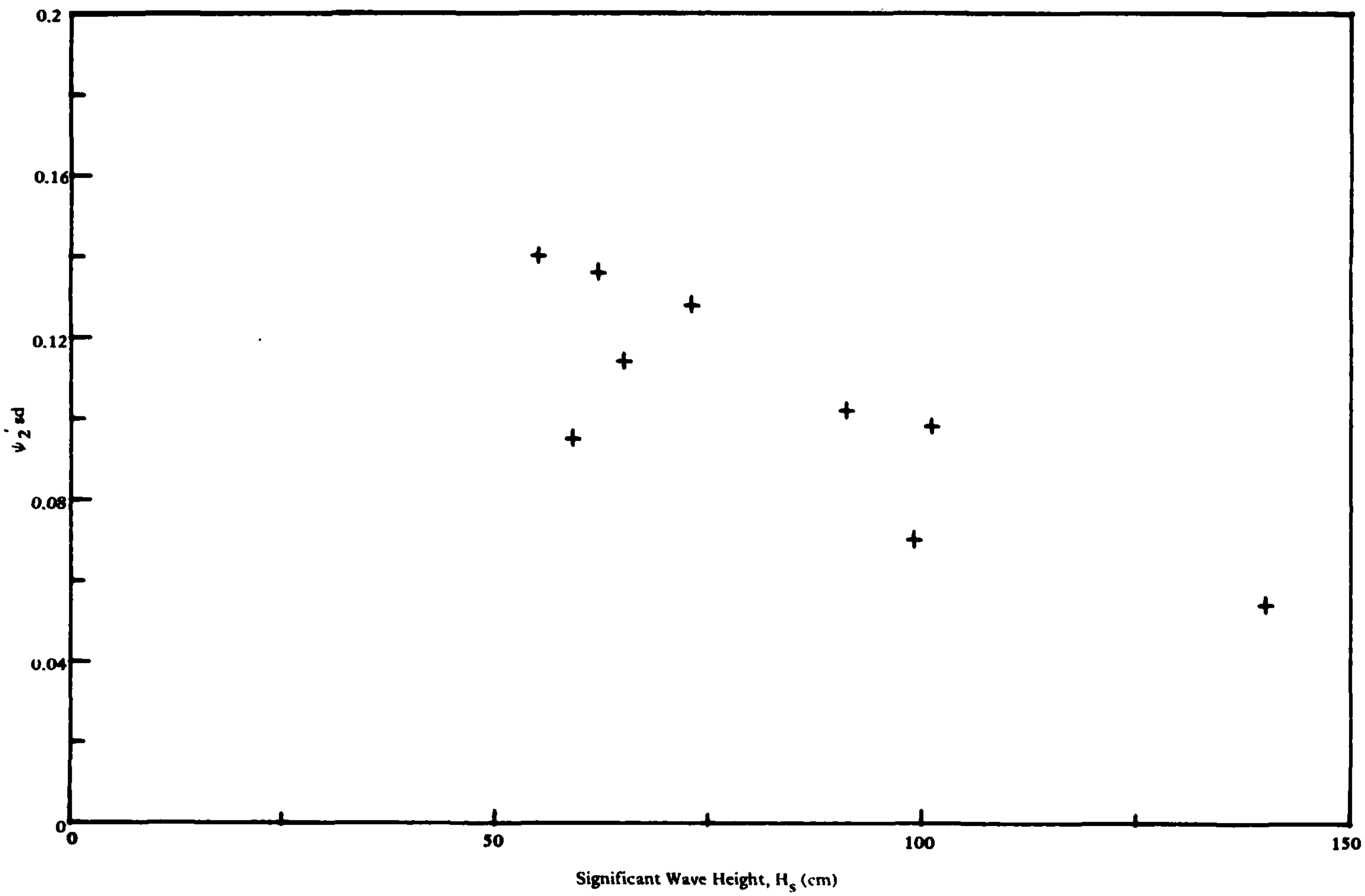

Figure 12. Average surfzone values of the standard deviation ψ_2'sd, versus significant wave height computed from single 64-minute records.

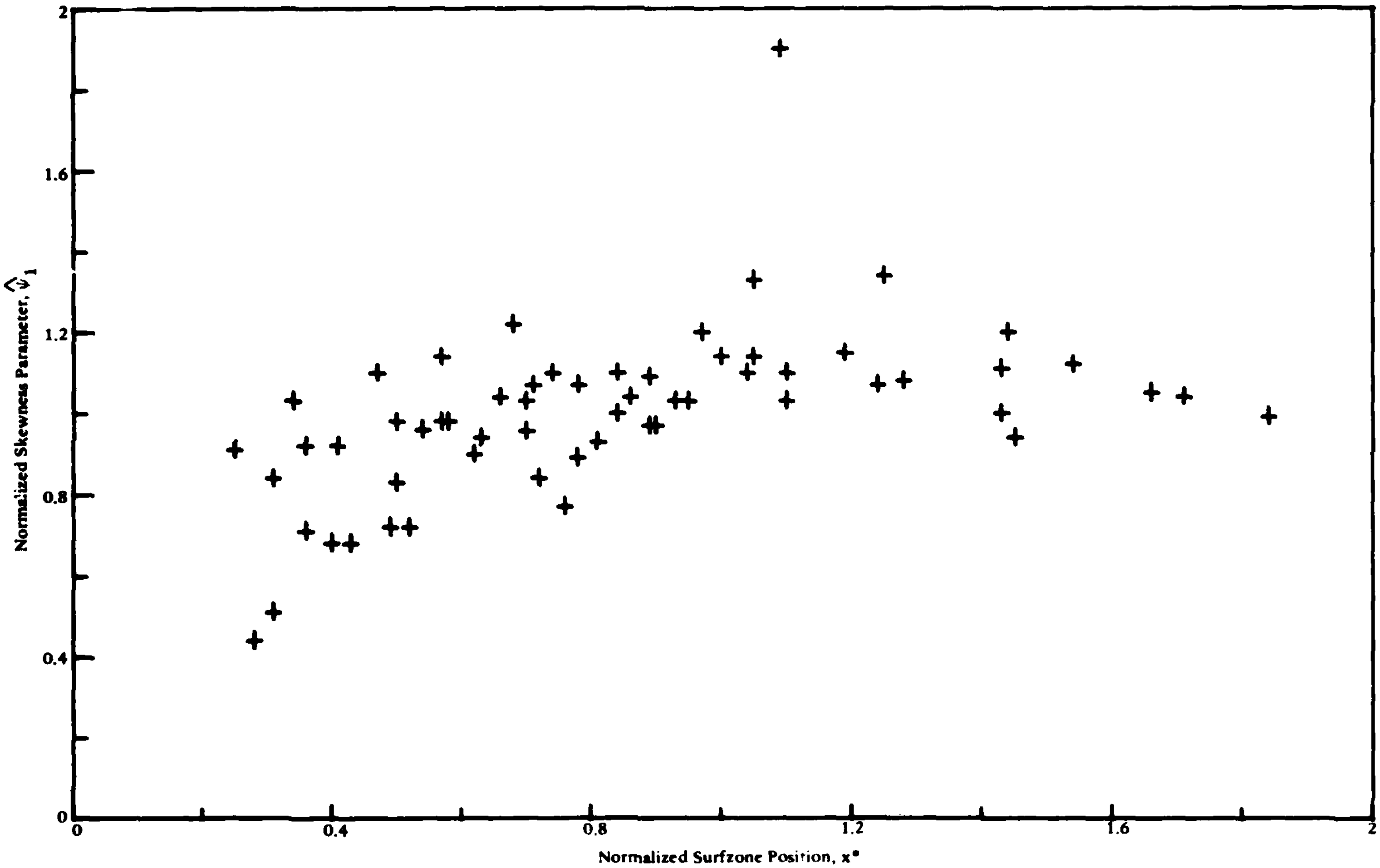

Figure 13. Surfzone distribution of the normalized skewness parameter ψ_1 computed from single 64-minute records using 7 different current meters and 9 different days of data.

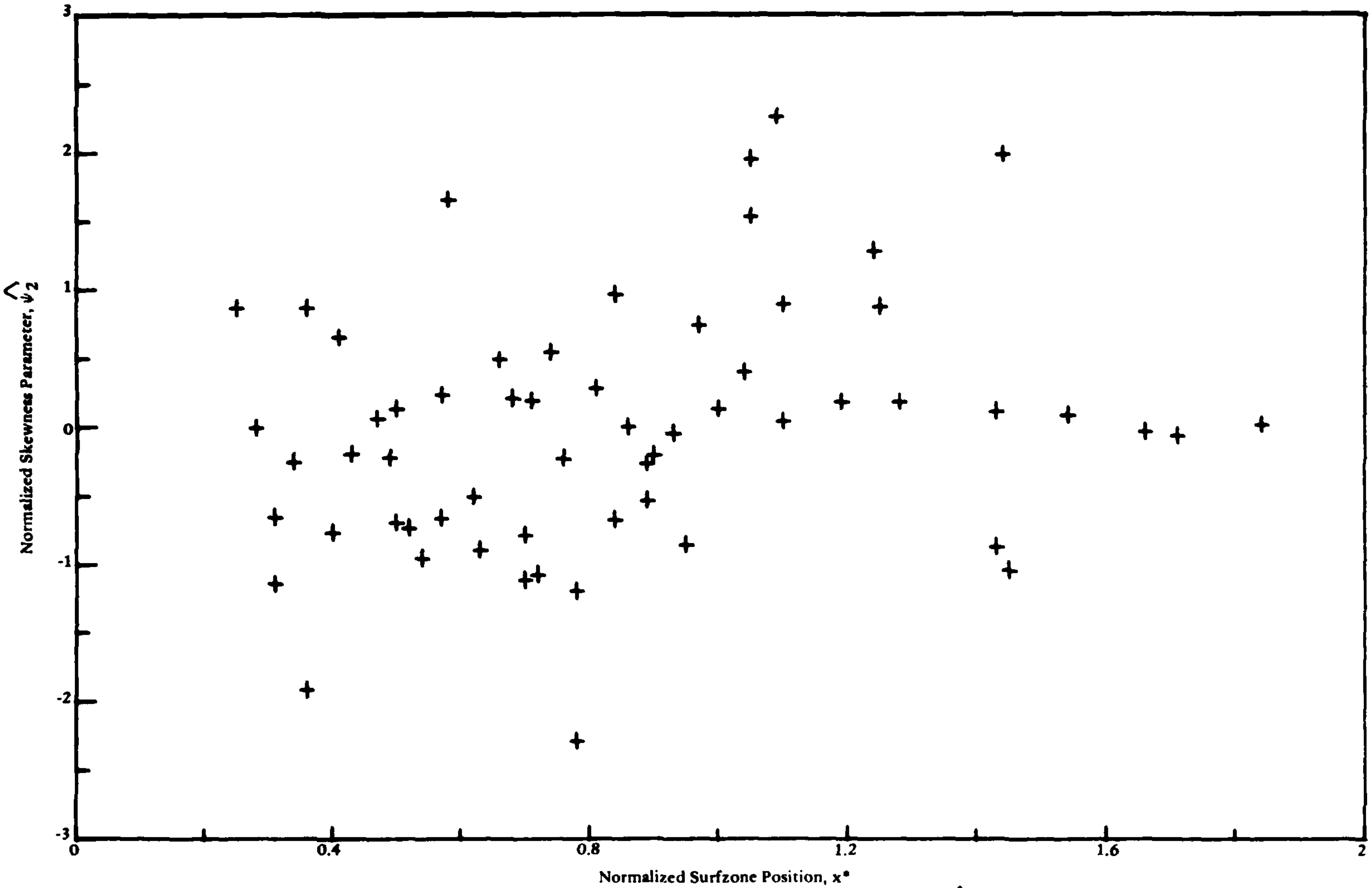

Figure 14. Surfzone distribution of the normalized skewness parameter $\hat{\psi}_2$ computed from single 64-minute records using 7 different current meters and 9 different days of data.

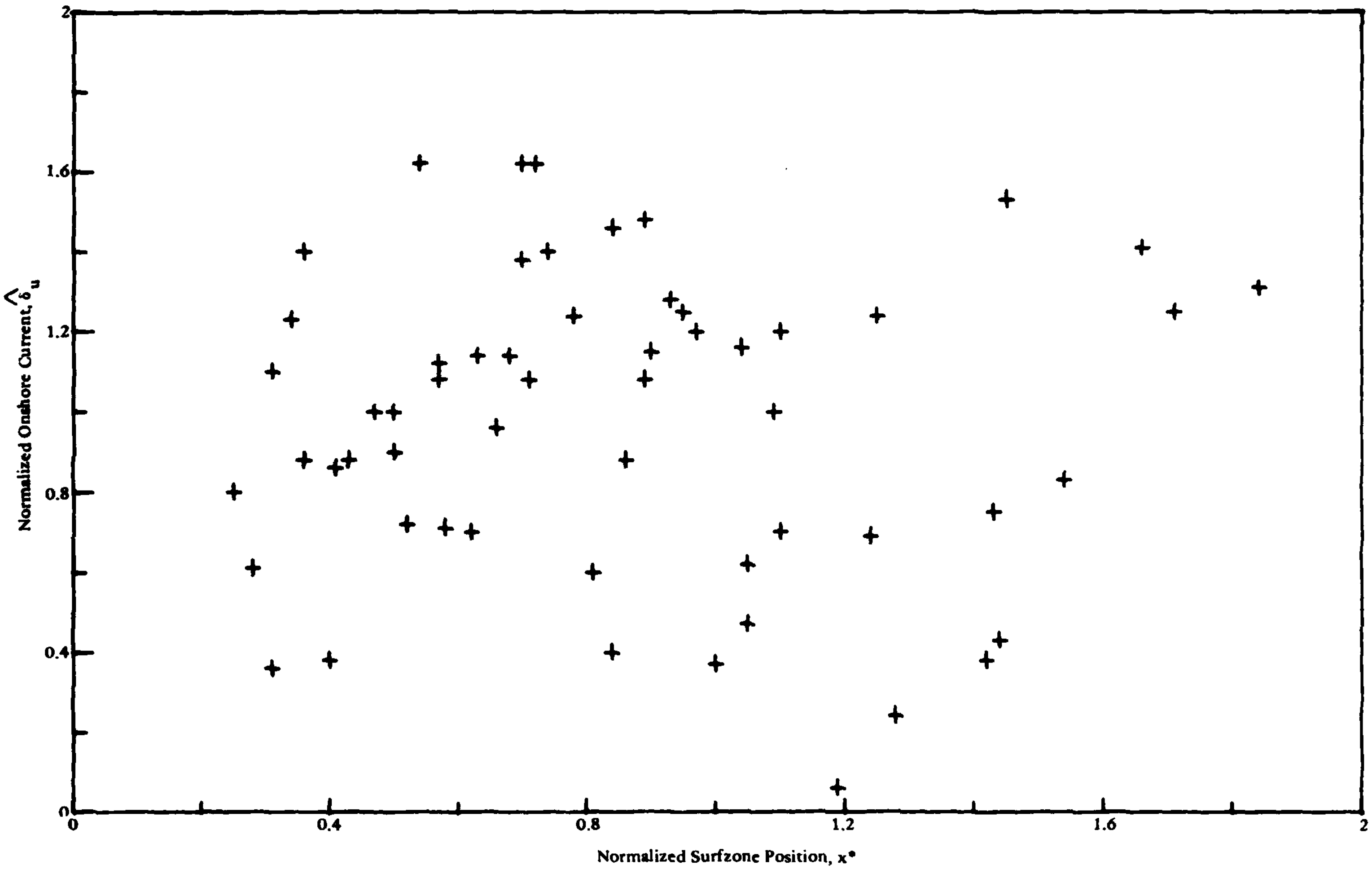

Figure 15. Surfzone distribution of the normalized onshore current $\hat{\delta}_u$ computed from single 64-minute records using 7 different current meters and 9 different days of data. Note that a positive normalized current is directed offshore.

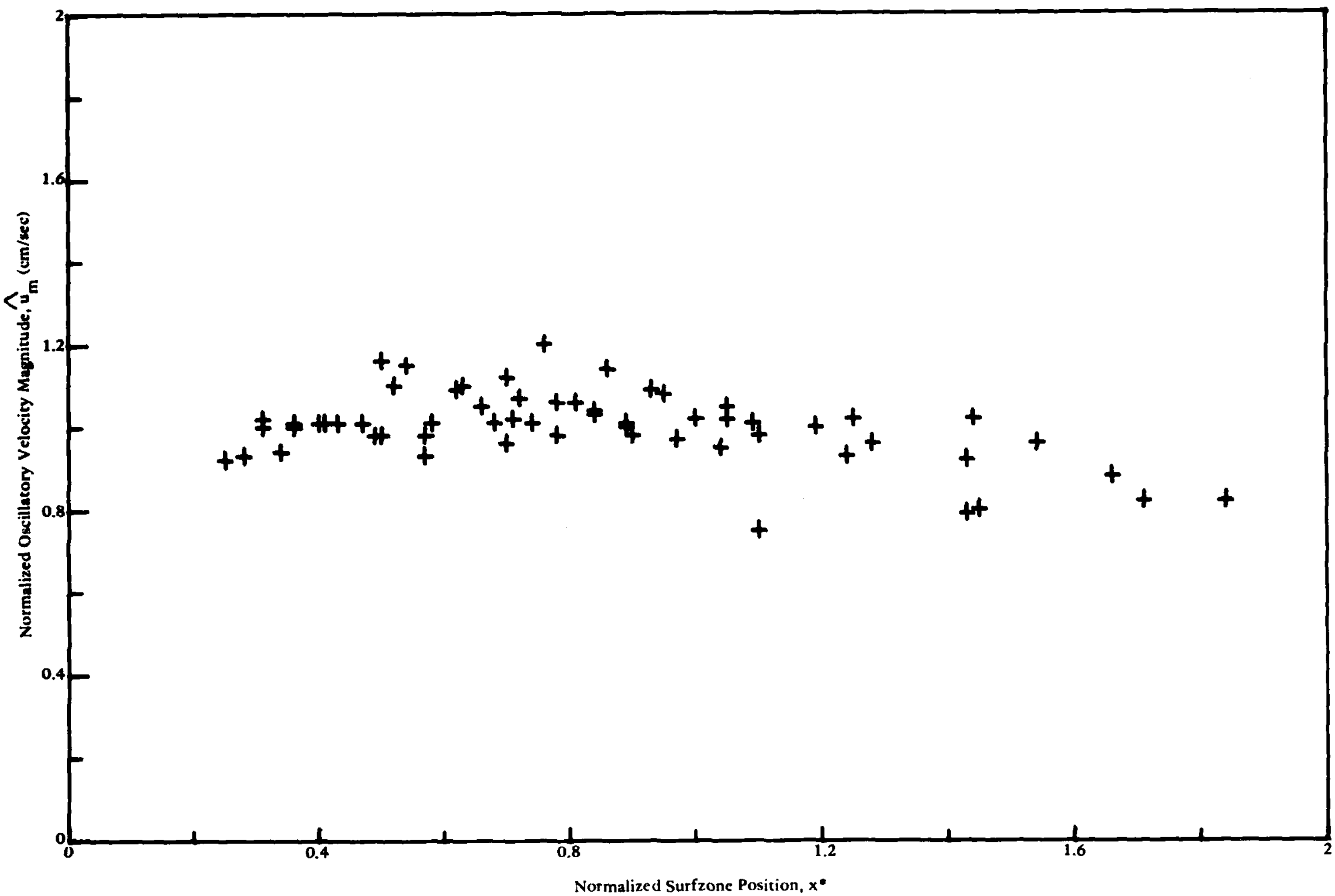

Figure 16. Surfzone distribution of the normalized orbital velocity magnitude $\hat{u}_m$ computed from single 64-minute records using 7 different current meters and 9 different days of data.

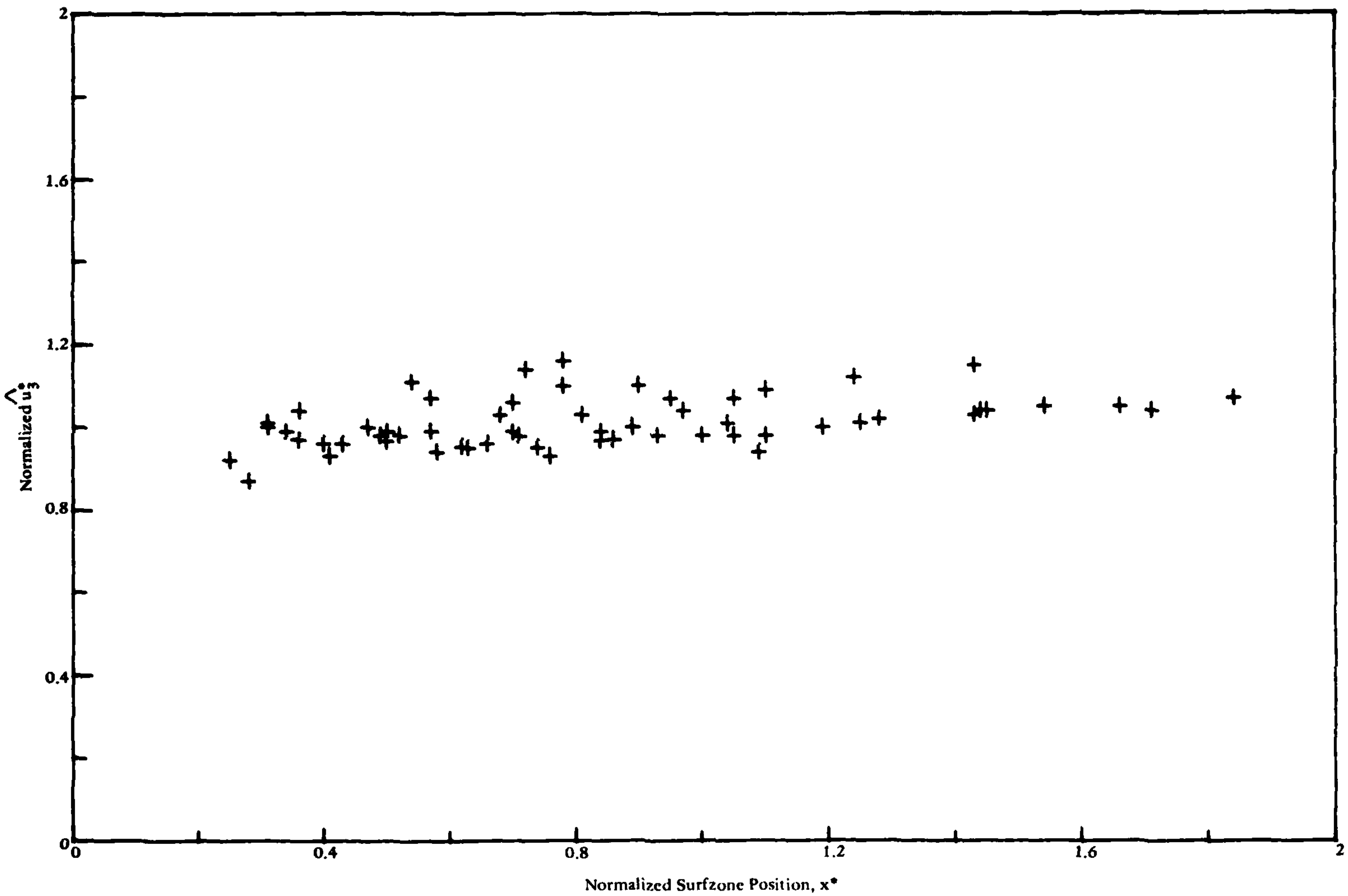

Figure 17. Surfzone distribution of the normalized parameter $\hat{u}_3^*$, computed from single 64-minute records using 7 different current meters and 9 different days of data.

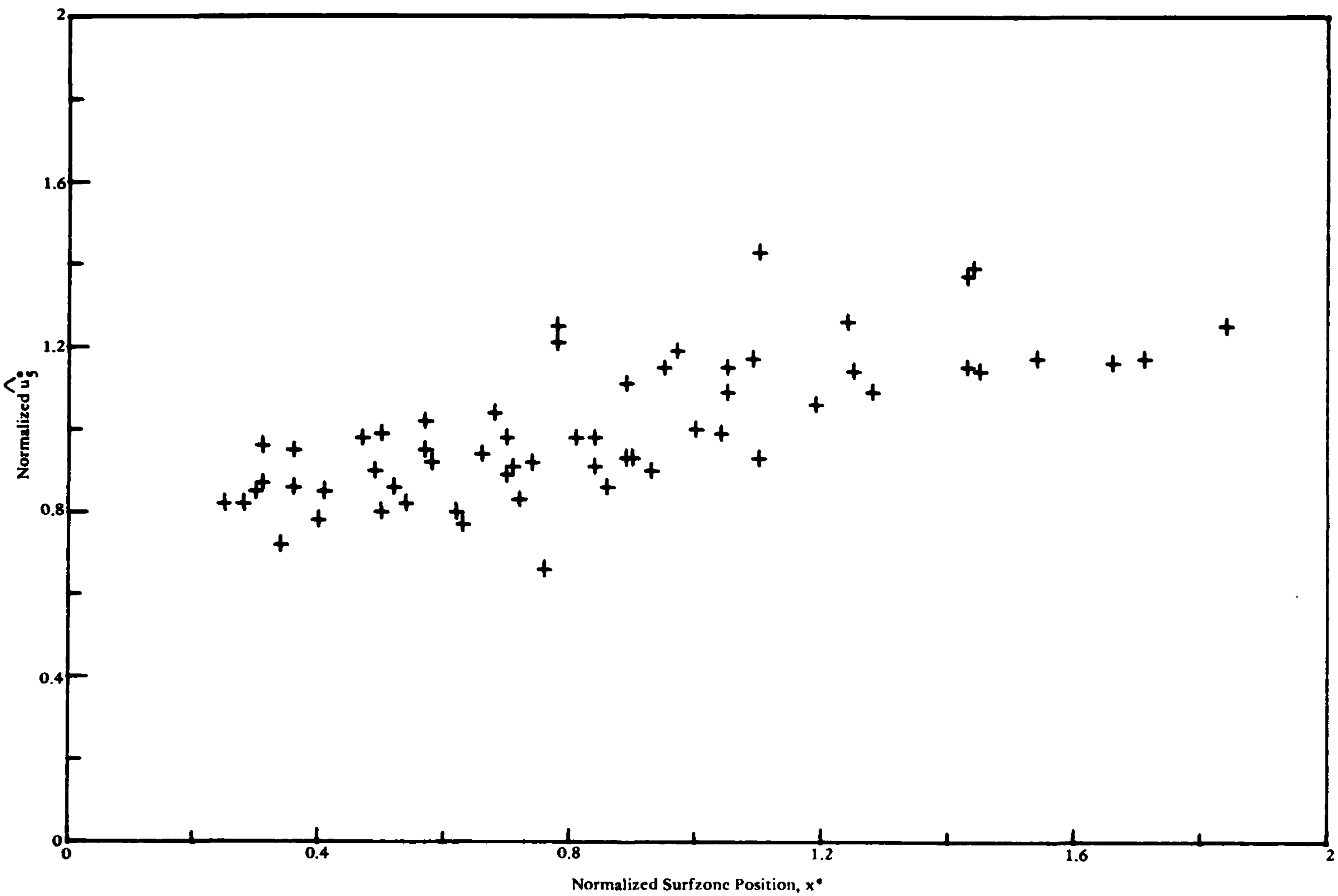

Figure 18. Surfzone distribution of the normalized parameter $\hat{u}_\zeta^*$, computed from single 64-minute records using 7 different current meters and 9 different days of data.

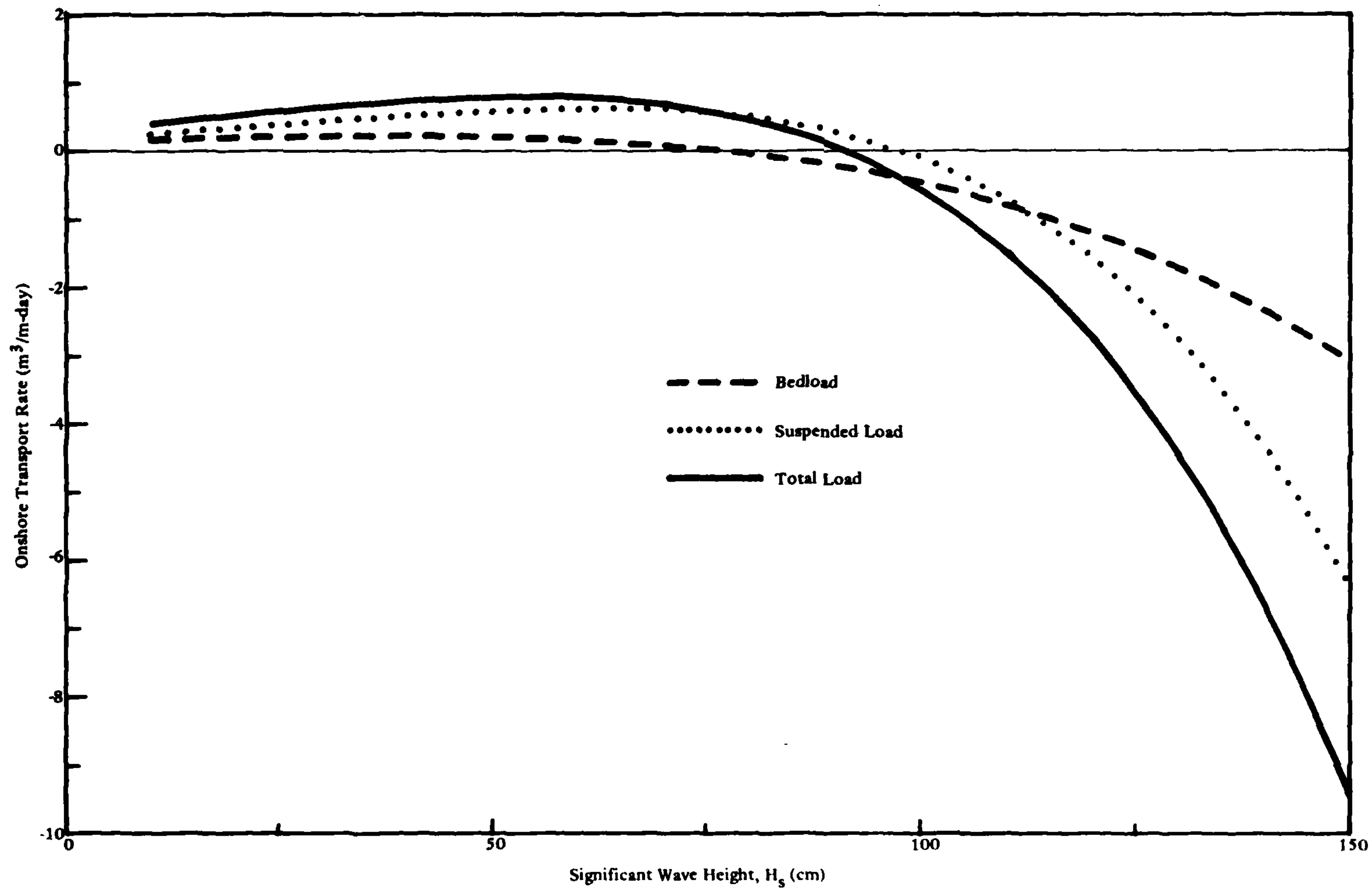

Figure 19. Predicted on-offshore sediment transport rate as a function of significant wave height. The individual contributions of the bedload and suspended load transports to the total transport are shown by the dashed and dotted lines, respectively. The point of neutral transport (equilibrium) occurs at a significant wave height of 90 cm.

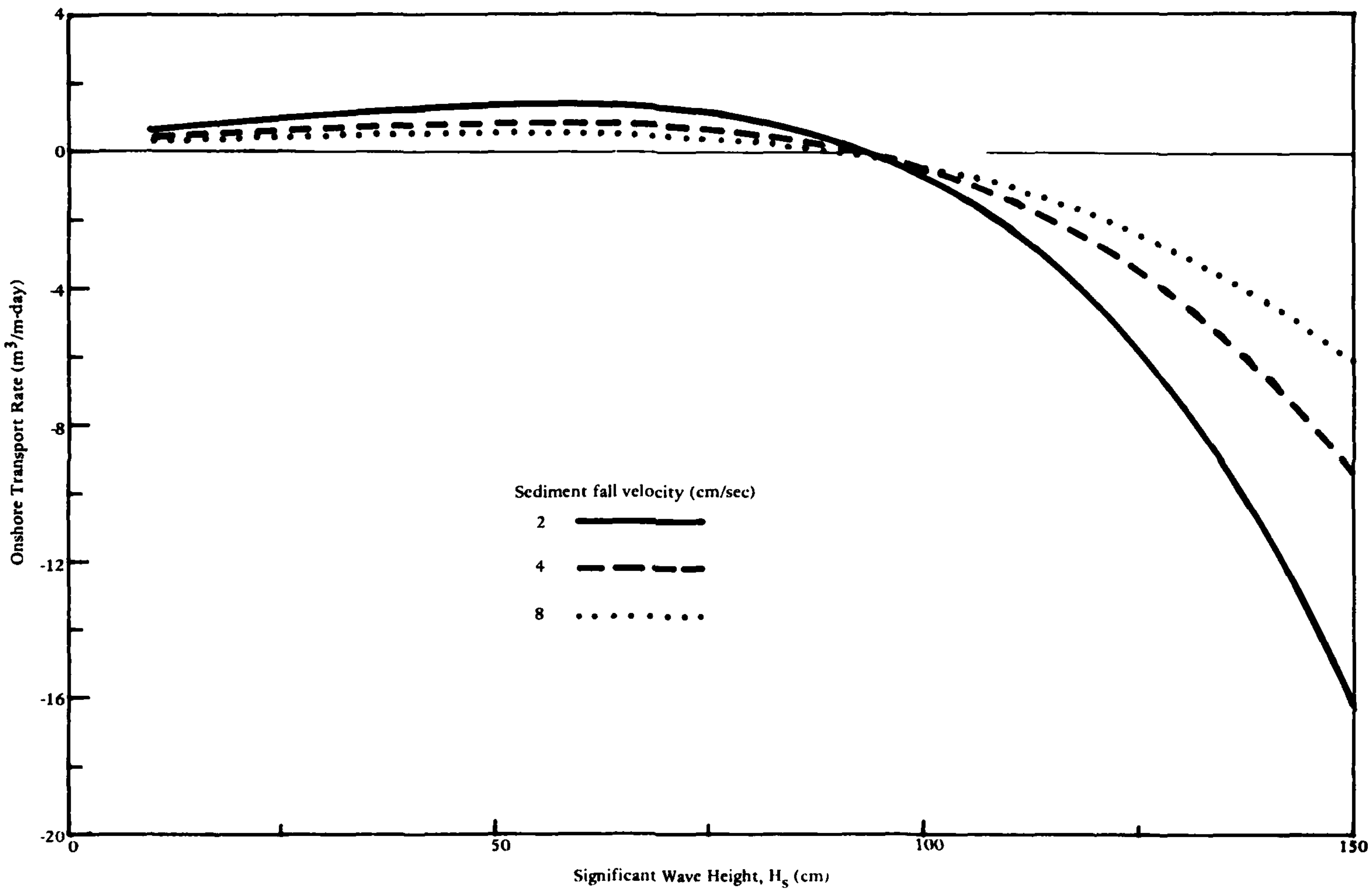

Figure 20. Predicted total load on-offshore sediment transport rate as function of significant wave height and sediment fall velocity. Greater rates of transport are found for smaller sized sediments.

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